PB98-118599

EVALUATION OF FALLING WEIGHT DEFLECTOMETER

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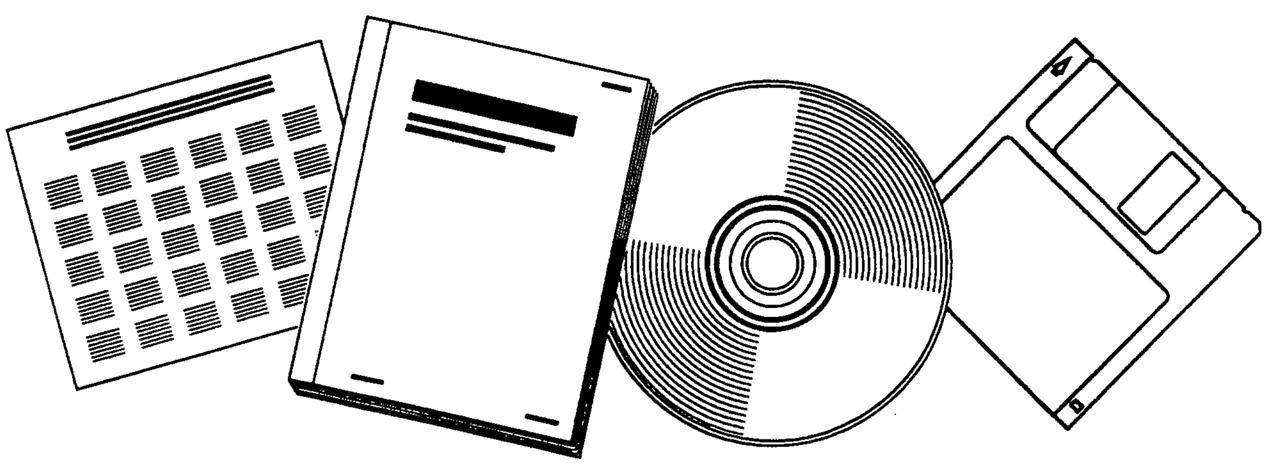

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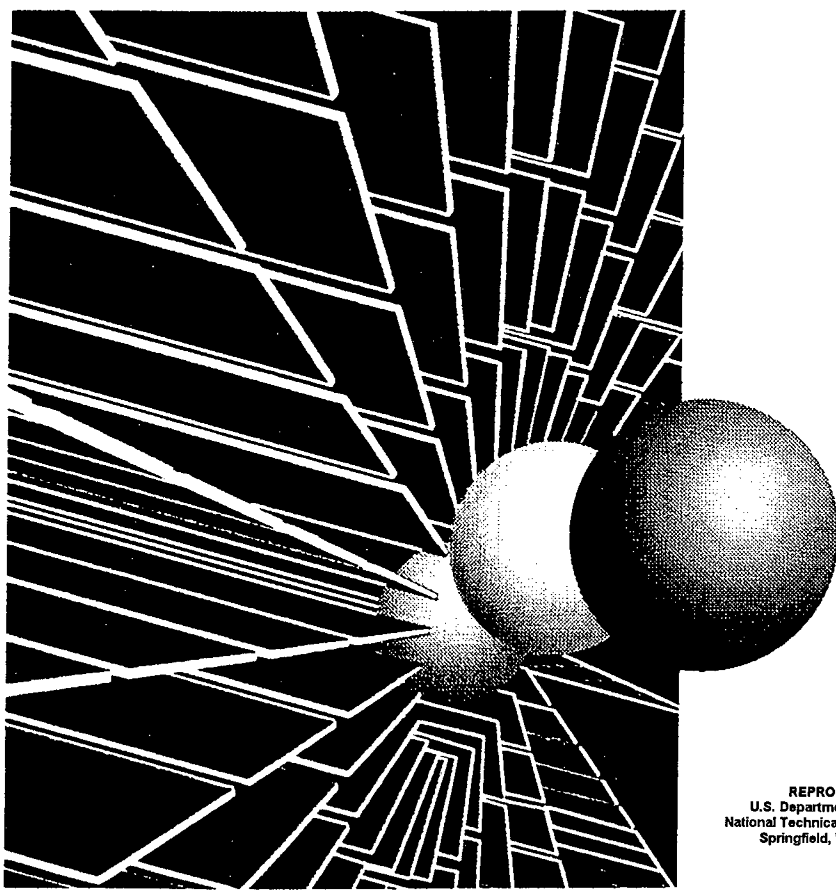
Evaluation of Falling Weight Deflectometer

Final Report



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The investigation was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

16. Abstract

The objective of this research investigation was to evaluate the Falling Weight Deflectometer (FWD), the test procedures used in its field data acquisition, and the mechanical-empirical equations which employ this non-destructive testing (NDT) deflection data to calculate the effective structural capacity of in-service pavements.

It was determined that the Falling Weight Deflectometer can be used to estimate/calculate the in-situ structural capacity of existing pavements. Test procedures and recommendations for its use are presented in this report.

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EVALUATION OF THE FALLING WEIGHT DEFLECTOMETER

Evaluation of Non-Destructive Testing (NDT) equipment: the Falling Weight Deflectometer (FWD), its testing procedures, and the mechanistic-empirical equations used in the calculation of the effective structural capacity of in-service pavements.

INVESTIGATION NUMBER
RI88-2

MISSOURI HIGHWAY AND RESEARCH STUDY 15B
HPR-15B
FORMERLY HPR-43

FINAL REPORT

PREPARED BY
MISSOURI DEPARTMENT of TRANSPORTATION
RESEARCH DEVELOPMENT and TECHNOLOGY DIVISION

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Jefferson City, Missouri
Date: November 9, 1994

The opinions, findings, and conclusions expressed in this publication are those of the Missouri Department of Transportation.

EXECUTIVE SUMMARY

The objective of this research investigation was to evaluate the Falling Weight Deflectometer (FWD), the test procedures used in field data acquisition, and the mechanistic-empirical equations used to calculate the effective structural capacity of in-service pavements from the Non-Destructive Testing (NDT) deflection data.

In December of 1988 the Missouri Department of Transportation (MoDOT) purchased a Dynatest Model 8000 FWD. And, in the spring of 1989 began experimentally testing pavement.

In the early years of this investigation the data acquisition procedures were not uniform. The deflection sensor spacing setups, weight drop heights, number of drops per test section, and intervals of testing were frequently changed. Since then the Strategic Highway Research Program (SHRP) Long Term Pavement Performance (LTPP), the American Society of Testing and Materials (ASTM), and the American Association of State Highway and Transportation Officials (AASHTO) have set standards for NDT deflection data acquisition for the FWD. The FWD field testing procedures depicted in this investigation will try to comply with the above mentioned standards.

Once deflection data is acquired from the field it is used to estimate the in-situ structural capacity of the pavement. This investigation evaluated two of the numerous backcalculation programs, Chapter 5 (Rehabilitation Methods With Overlays) of the 1993 AASHTO Guide For Design of Pavement Structures, and the DARWin Pavement Design program which employs the equations of the 1993 AASHTO Design Guide.

The two backcalculation programs were ELMOD\ELCON and MODULUS. There were limited indications that the Modulus program provided more reasonable and consistent results, therefore it was the backcalculation program of choice used in this investigation.

Chapter 5 of the 1993 AASHTO Design Guide, and the DARWin program, present procedures to utilize NDT deflection data to estimate the in-situ structural capacity of the pavement and to calculate the rehabilitative overlay thickness to upgrade the existing structure. This investigation has found that these procedures, and the equations which are employed in these procedures, are presently the best means of estimating the effective structural capacity of in-situ pavements from FWD NDT deflections.

Some of the conclusions of this investigation are as follows:

The FWD NDT deflections can be used to estimate the in-situ structural capacity of pavements.

The backcalculation of estimated moduli values of pavement layers can be accomplished with the program "Modulus".

Deflection basin parameters, such as the deflection directly under the load plate (d_0), the deflection basin area, and the radius of curvature of the deflection basin could be used in a data base for an inventory tool. This data base should have graphical capabilities so as to display the deflection basin parameters versus the log mile location of the pavement. This data base should be structured so it can be eventually incorporated into a Pavement Management System (PMS).

The effective structural capacity of the pavement can be estimated using the 1993 AASHTO Pavement Design Guide and the pavement design program "DARWin". The DARWin program can be used to analyze pavements at a project level.

MoDOT should not consider this topic completely evaluated. There are daily changes in (NDT) equipment and the processes that use the FWD's output. Further improvements of mechanistic-empirical analysis and design from NDT data is inevitable. And, a simpler means to incorporate FWD NDT results into a PMS system will surely be innovated.

Since its infancy, the FWD and the backcalculation process/procedures have evolved to the point where usable information on the structural capacity of in-service pavements can be obtained.

Some of the recommendations from this investigation are as follows:

MoDOT should institute a testing program with the FWD that could provide inventory and project level information. The interstate and primary routes should all be tested and the data inventoried into a data base with graphical capabilities. This testing program should be on a two year interval and conducted as outlined in this report.

The use of the FWD and the computation of the needed output from the FWD should remain in the control of someone familiar with the entire process and its shortcomings.

MoDOT should continue to use the Dynatest FWD to promote data uniformity and staff familiarity with the equipment and its expected results.

MoDOT should establish its own absolute calibration center if more FWD units are purchased.

MoDOT should continually review changes in this field and use any collected information, internal or external, to update the proposed process.

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LIST OF ABBREVIATIONS

A	Factor to convert PCC thickness deficiency to AC overlay thickness
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
a_e	Radius of the stress bulb at the subgrade-pavement interface
ABS	Average Absolute Relative Difference
AC	Asphalt Concrete
AC/PCCP	Asphalt Concrete overlay of Portland Cement Concrete Pavement
ASCI	American Standard Code for Information Interchange
ASTM	American Society of Testing and Materials
ARAN	Automatic Road Analyzer
C	Correction factor to the Backcalculated M_r
C_d	Coefficient of Drainage
d_0	FWD deflection under the load plate
d_{36}	FWD deflection at 36 inches away from the center of the load plate
D	Depth of existing pavement
D_f	Required slab thickness for future traffic
D_{eff}	Effective slab thickness of existing pavement
D_{ol}	Required thickness of AC overlay
D_{pcc}	Depth of existing PCCP slab
DMI	Distance Measuring Instrument
E_{ac}	Elastic Modulus of AC layer
E_p	Effective Modulus of the Pavement
E_{pcc}	Elastic Modulus of Portland Cement Concrete

ESAL's	Equivalent Single 18 kip Axles Loads
F_{ac}	AC Quality Adjustment Factor
F_{dur}	Durability Adjustment Factor
F_{fat}	Fatigue Damage Adjustment Factor
F_{jc}	Joint and Crack Adjustment Factor
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
GPS	General Pavement Studies
HPR	Highway Planning and Research
J	Joint load transfer value
k-value	Subgrade bearing capacity in pounds per cubic inch
k_{eff}	Effective Subgrade bearing capacity (takes into account seasonal variations)
LS	Loss of Support
LT	Joint Load Transfer, percent
LTPP	Long Term Pavement Performance
MHTD	Missouri Highway and Transportation Department
mil	1 mil = 0.001 inch
M_r	Subgrade Resilient Modulus
M_{Reff}	Effective Subgrade Resilient Modulus (takes into account seasonal variations)
NDT	Non-Destructive Testing
PCC	Portland Cement Concrete
PCCP	Portland Cement Concrete Pavement
PMS	Pavement Management System
PSI	Present Serviceability Index
R%	Overlay Design Percent Reliability

RMS	Root Mean Square
S_0	Overall Standard Deviation
S_c'	PCC Modulus of Rupture
SHRP	Strategic Highway Research Program
SN_{eff}	Effective Structural Number of existing pavement
SN_f	Required Structural Number for Future traffic
SN_{ol}	Required Overlay Structural Number
SPS	Specific Pavement Studies
TTI	Texas Transportation Institute
W_{18}	Accumulative design ESAL's in the design lane for the design life of the project

ABSTRACT

The objective of Research Investigation No. RI88-02 was to evaluate the Falling Weight Deflectometer (FWD), the test procedures used in its field data acquisition, and the mechanistic-empirical equations which employ this Non-Destructive Testing (NDT) deflection data to calculate the effective structural capacity of in-service pavements.

It was determined that the Falling Weight Deflectometer can be used to estimate the in-situ structural capacity of existing pavements. Test procedures and recommendations for its use are presented in this report.

OBJECTIVES

The objective of this research investigation was to evaluate the Falling Weight Deflectometer (FWD), testing procedures, and the mechanistic-empirical equations used in the estimation of the effective structural capacity of existing pavements. The intent of this evaluation was to try to find a usable, reliable, and efficient tool that could quantitatively inventory the structural capacity of in service pavements. Subsequent use of this knowledge could be inventory data in our Pavement Management System (PMS), and/or to use as a viable alternative to evaluate existing pavement structures at the project level.

This study included the following:

1. Evaluate the Falling Weight Deflectometer, procedures, and data collection.
2. Evaluate backcalculation process and programs that determine in-situ moduli.
3. Review Chapter 5 of the 1993 AASHTO Guide for Design of Pavement Structures and the pavement design program "DARWin".
4. Determine the structural capacity of typical in service pavements from non-destructive testing deflections.
5. Tentative implementation of subsequent knowledge.

INTRODUCTION

The Missouri Department of Transportation (MoDOT), in December of 1988, purchased an FWD to determine if it was a usable, reliable, and efficient avenue for determining the structural capacity of in-service pavements. Previously, engineering judgement, destructive sampling and testing, or a standard rehabilitation design were the only tools used by MoDOT to determine the rehabilitation design of a pavement. The rehabilitation of pavements is traditionally triggered by functional factors, but once this occurs then an analysis of the pavement's structural factors is necessary to determine the extent and type of rehabilitation best suited to the department's needs.

Other state highway agencies have used Non-Destructive Testing (NDT) for many years, most common was the Benkelman Beam. MoDOT used the Benkelman Beam on research test sites as part of the AASHO Satellite program beginning in the 1960's. The practice of using the Benkelman beam for testing to determine the rehabilitation needs was never adopted by MoDOT. The adoption of the AASHTO Design Guide and a desire to initiate PMS has prompted the need for NDT.

The development of the Falling Weight Deflectometer (FWD), Roadrater, and other similar automated deflection testing equipment created the opportunity for highway engineers to access information about the structural factors of in-service pavements.

MoDOT purchased a Dynatest FWD Model 8000 to begin evaluating:

1. Equipment
2. Test Procedures
3. MoDOT Pavements
4. Backcalculation Programs to Determine Moduli
5. Possible Implementation Procedures

During a three year period, 1989 to 1991, testing of numerous test sections was performed three times a year. In 1991 and part of 1992, nine test sites were tested on a monthly basis to determine seasonal effects. This data base of information is now being evaluated to answer ongoing questions concerning NDT application.

The following is a report of the how, when, where and why concerning the use of a FWD for NDT in Missouri.

NDT TEST EQUIPMENT SELECTION

The choices of NDT equipment for deflection testing were numerous. They included the Dynatest FWD, Kaub FWD, Roadrater, and the Benkelman Beam. It was determined by the Strategic Highway Research Program (SHRP) that for their deflection testing, the Dynatest FWD would be the choice. An FHWA report came to the conclusion that the FWD, particularly the Dynatest, would be one of the best NDT equipment choices *(1)*. The Dynatest FWD best simulates a dynamic 18 Kip axle load of a tractor-trailer by imparting a 9 Kip, half of an 18 Kip axle, dynamic load onto the pavement for approximately 25 to 30 milliseconds. The 5.9 inch contact plate radius of the Dynatest FWD when used with the 9 Kip load produces approximately 82 psi which is the contact pressure of most tractor-trailer truck tires. In comparison to other FWD's the Dynatest FWD has one of the smallest measurement of error and one of the shortest test times on a per measurement basis *(1)*. Contacts with Kaub for competitive bidding yielded no alternative bid against the Dynatest equipment so the choice was made to purchase a Dynatest Model 8000 FWD to use for this evaluation. It was received December 7, 1988.

The major additions to the standard Dynatest Model 8000 FWD were: an automated air thermometer, an automated surface thermometer, a distance measuring instrument (DMI), and updating of the Dynatest Field Program used in data collection.

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FWD FIELD TESTING PROCEDURE

When performing FWD testing for the Strategic Highway Research Program (SHRP) Long Term Pavement Performance (LTPP) program the tests will be in accordance with the Manual for FWD Testing in the LTPP Program *(2)*. Testing for MoDOT, to obtain inventory and project level information, will be conducted as follows.

1. INTERVAL & LOCATION

The test interval for deflection basin tests will be every 0.25 mile on full depth flexible pavements, existing asphalt concrete overlay of PCC pavements, and existing asphalt concrete overlay of fractured PCCP slab. Deflection basin tests on rigid pavements, such as full depth concrete and existing bonded and unbonded concrete overlays, will be tested at the mid panel of the slab nearest to the 0.25 mile increment. And load transfer tests on the joints of rigid pavement will be performed on the lead in joint which accompanies the mid panel nearest to the 0.25 mile increment. The location, for both flexible and rigid pavement, of the test will be in the outer wheel path of the driving lane. The 1993 AASHTO Guide For Design Of Pavement Structures recommends testing intervals between 100 to 1,000 feet in the outer wheel path *(3)*. ASTM D4695, Type II testing routine, used in the determination of overlay design, endorses a 100 to 500 foot interval for flexible pavements and a 100 foot interval for rigid pavements both in the outer wheel path. The Type I testing routine, used for the general overview of the pavement's condition, endorses a 500 to 1000 foot test interval in the outer wheel path *(4)*. The proposed 0.25 mile increment location was selected to coincide with 0.25 mile increment that is presently used for friction testing of the pavements. This slightly exceeds the recommended 1,000 foot interval, but is best suited for our purpose. For test location repeatability the test point intervals will be tied to the MHTD log mile system.

<u>2. DROP HEIGHT, LOAD, AND SEQUENCE.</u>

The drop pattern used for deflection basin tests will be five drops from drop height number 2, which is equivalent to a 9000 pound load, with the first two drops used for seating and no data stored. Only the peak deflections will be recorded, the deflection time history will not be recorded. The 9000 pound load is recommended by the ASSHTO Design Guide *(3)*. In case of small amounts of debris on the pavement the two seating drops are used to seat the buffer pad and sensors to the pavement, which will reduce erroneous data due to improperly seated sensors. The three recorded drops for one test are used to reduce random error and to check if deflection variance is within a 5% tolerance. ASTM D4694 recommends at least two drops per test *(4)*. The total history will not be recorded because it consumes a large amount of computer space and at this time is not essential for the calculation of the structural capacity of the pavement.

<u>3. SENSOR SPACING</u>

Sensor spacing for deflection basin tests will be in accordance with the SHRP Manual for FWD Testing in the LTPP Program. The sensor spacing for deflection basin testing is 0, 8, 12, 18, 24, 36, & 60 inches from the load plate. The sensor numbers that correspond to the spacings are 1, 2, 3, 4, 5, 6, & 7 respectively. Deflection basin shape ranges significantly from steep basins for weak flexible pavements to shallow basins for stiff rigid pavements. The shape varies most significantly within the first three feet of the load plate therefore the first three feet contains the most sensors *(2)*. Sensor spacing for load transfer test, on rigid pavement joints, will be in accordance with the SHRP Manual and the AASHTO Pavement Design Guide. The sensor spacing will be -12, 0, 12, 18, 24, 36, & 60 inches from the load plate. The sensor numbers which correspond to the spacings are 2, 1, 3, 4, 5, 6, & 7 respectively.

4. EXISTING PAVEMENT CROSS SECTION

Layer thickness data is one of the most important elements relative to mechanistic analysis and mechanistic-empirical design *(5)*. The mechanistic-empirical equations in Chapter 5 of the 1993 AASHTO Design Guide require pavement thickness to calculate Effective Structural Number (SN_{eff}) for flexible pavements and Slab Thickness to Carry Future Traffic (D_f) for rigid pavements. Pavement layer thickness can be determined from accurate construction data history and/or representative core samples of the roadway structure. When historic pavement layer information is used and the validity of the backcalculated moduli, SN_{eff}, D_f, or overlay thickness is suspect, core samples of the pavement should be obtained to validate the actual in-situ thickness of the pavement layers. Therefore, historical pavement cross section data should be obtained before the pavement is to be tested.

5. MATERIALS TESTING & PAVEMENT DISTRESS SURVEY

Materials testing and the pavement distress survey should be performed. Materials testing shall be performed at one mile increments when needed to verify historic cross section data. The SHRP Distress Identification Manual will be used to categorize and quantify distress types and conditions. This condition survey is needed to determine the Effective Slab Thickness (D_f) on Asphalt Concrete over Portland Cement Concrete Pavements (AC/PCCP) and Portland Cement Concrete Pavements (PCCP). For full depth Asphalt Concrete (AC) pavements, material testing and a pavement distress survey should be performed to ascertain if the pavement has stripping and serviceability problems.

6. AMBIENT AIR AND PAVEMENT SURFACE TEMPERATURE

Another very important parameter in mechanistic analysis and mechanistic-empirical pavement overlay design is the AC mix temperature. It is important because the Modulus Of Elasticity of asphalt (E_{ac}) is temperature sensitive. There are two ways to obtain the mid-depth pavement temperature of flexible pavement layers. One way is to physically measure the mid-depth temperature, and the other way is to estimate it.

To physically measure the temperature, a one inch diameter hole must be cored into the pavement to the approximate mid-depth location. A non petroleum based fluid, other than water, is placed in the bottom inch of the hole. A temperature probe is inserted into the fluid and readings are taken.

To estimate the mid-depth temperature, regression equations and graphs generated from the research performed by H.F. Southgate can be used *(6)*. This estimation requires a 5 day average air temperature, a pavement surface temperature, and the mid-depth thickness. For MoDOT the 5 day average air temperature can be obtained from the Project Office nearest to the FWD testing. The pavement surface temperature can be automatically recorded by an infrared thermometer mounted on the FWD *(3)*. See Appendix (A) for a graph of E_{ac} versus AC temperature which was plotted using MoDOT asphalt mix values and the Asphalt Institutes regression equation. Also see Appendix (B), which is an excerpt from MoDOT Research Investigation RI91-09A, for the 5 day average air plus pavement surface temperature graphs and regression equations to estimate the mean AC mix temperature.

7. WEATHER RESTRICTIONS

In FWD testing there are some weather restrictions that should be adhered to in order to obtain accurate and reliable data. The list is as follows:

1. No testing when the subgrade is frozen, extremely low deflections will result and erroneous data will be collected.
2. To avoid joint interlock and slab curling, rigid pavement should be tested when the ambient air temperature is between 35 and 85 degrees Fahrenheit, or on overcast days, or on nights when there is not extreme temperature variations between night and day.
3. Testing should be avoided immediately after excessive rainfall so water under the pavement has a chance to dissipate.
4. Do not measure joint load transfer when the ambient air temperature is greater than 85 degrees Fahrenheit (*3*).
5. When testing composite AC/PCC pavements, if the 5 day average air temperature plus pavement surface temperature is used to estimate the mean AC mix temperature of an asphalt layer, discontinue this procedure when the estimated mean temperature of the mix is greater than 85 degrees F. After an AC temperature of 85 degrees the mean asphalt temperature should be obtained manually. This temperature restriction was determined from MHTD Research Investigation RI91-09A. Appendix C is an excerpt from RI91-09A. (See Appendix C)

8. DATA COLLECTION FILE SIZE & FILE NAME CONVENTION

To be compatible with the computer program "DARWin", developed by ERES Consultants Inc. for AASHTO, the FWD data files shall be limited in size to 500 drops per file *(7)*. This will allow the use of the file at the project level. At the inventory level, this will allow for approximately 40 miles of pavement to be tested at 3 drops per test at 0.25 mile increments. When testing rigid pavement two separate FWD data collection files will be recorded. One for the deflection basin test and one for the load transfer test. This is due to the different sensor spacing set up, different analysis of the data, and to stay compatible with the "DARWin" program. Tentative file name convention will be as follows:

1. The first six digits of the FWD data file will be the Job or Project number which is being tested.
2. The last two digits will be designated DB for deflection basin test or LT for load transfer test.

9. CALIBRATION

Relative Calibration of the sensors is performed on a monthly basis in accordance with SHRP-P-652 guidelines and the SHRP Software FWDCAL2. This process involves stacking the deflection sensors in a special stand, so that all will simultaneously measure the deflection of the pavement at the same point. The differences in measured deflections are addressed by assigning an appropriate multiplier for each sensor so the deflection readings are the same for each sensor *(8)*.

Reference Calibration of the load cell is on an annual basis in accordance with SHRP-P-652 protocol and SHRP Software FWDREFLC program.

BACKCALCULATION PROCESS AND PROGRAMS

1. BASIC HISTORY

The origin of layered elastic theory is credited to V.J. Boussinesq who published his work in 1885. He developed a closed form mathematical solution for computing stresses and deflections in a halfspace (soil) composed of homogeneous, isotropic, and linear elastic material. His development was for a single layer system under a point load *(9)*. In this approach, the stresses and deflections are calculated for a point load applied to the surface of a deep soil mass. Distance variables are expressed in terms of cylindrical coordinates, in which distance from a point load on the surface may be depicted as:

$$R^2 = r^2 + z^2$$

His equation for vertical deformation below the surface:

$$u_{zr} = \frac{P(1+u)}{2(3.14)E} \left[\frac{2(1-u)}{R} + \frac{z^2}{R^3} \right]$$

At (z=0, R=r) the surface deflection equation results:

$$u_{zr} = \frac{(1-u^2)P}{3.14(E)r}$$

Where P = Applied Load
u_{zr} = Deformation
E = Modulus of Elasticity
3.14 = Pi
u = Poisson's Ratio
r = Radial distance at which deformation is to be calculated

Now let $u = 0.50$, $d_r = u_{zr}$, and E = Resilient Modulus (M_r) and the following AASHTO Equation for determining the Resilient Modulus for AC overlays of full depth AC pavements results in *(3)*:

$$M_r = \frac{0.24P}{(d_r)r}$$

Where M_r = Backcalculated subgrade resilient modulus, psi
P = Applied load, pounds
d_r = measured deflection at radial distance r, inches
r = radial distance at which deflection is measured, inches

In 1926 Westergaard introduced the two layer system. In 1928 Love extended Boussinesq's work to a circular load on an elastic halfspace. In 1943 Burmister extended the one layer solution for a circular load to a two layer solution. In 1949 Odemark developed an approximate solution to calculate stress, strain, and displacement in a layered system. Odemark employed the concept of equivalent thickness, described in 1940 by Barber, and developed an equation to transform one layer of a multi-layer system into an equivalent thickness of another layer. This transformed section approach could then be applied in Boussinesq's single layer system *(9)*.
Odemark's transformed section equation is as follows:

$$h_e = h_1 \left[\frac{E_1}{E_2} * \frac{1-u_2^2}{1-u_1^2} \right]^{1/3} \qquad \frac{\text{Original x-sect.}}{\dfrac{h_1, E_1, u_1}{E_2, u_2}} = \frac{\text{Transformed x-sect.}}{\dfrac{h_e, E_2, u_2}{E_2, u_2}}$$

It has been found that the best agreement with the exact solution is obtained when the Poisson's ratio is assumed to be the same for both layers. The equation then reduces to:

$$h_e = h_1 \left[E_1/E_2\right]^{1/3}$$

Boussinesq's point load equation modified to approximate the effects of a circular distributed load is as follows:

$$d_z = \frac{(1+u)p*a}{E}\left[\frac{1}{\{1+(z/a)^2\}^{1/2}} + (1-2u)\left[\{1+(z/a)^2\}^{1/2} - z/a\right]\right]$$

Where p = load plate pressure, psi
E = Modulus of Elasticity, psi
a = Plate radius, inches
z = Depth below surface, inches
u = Poisson's ratio
d_z = Deflection, inches

These equations are the very basics of mechanistic backcalculation.(See Appendix (D) For Examples)
The rest of the documentation of the AASHTO design procedures, which employ derivations of Boussinesq's and Odemark's equations, can be found in Appendix L of the 1993 ASSHTO Pavement Design Guide *(3)*.

2. AVAILABLE SOFTWARE PROGRAMS

In 1951 Acum and Fox gave a solution for a three layer system. In the early 1950's the finite element method was introduced. In 1961 Jones and Peattie gave a solution for a three layer system. In 1963 commercial programs for five layer solution. In the 1970's widespread use of the layered theory was developed on main frame computers. And, in the 1980's to the 1990's personal computers are being used for backcalculation *(9)*.

There is a long list of programs that are now available for the backcalculation of in-situ moduli of the pavement structure. Each program has its advantages and disadvantages. Some of the primary factors which make the programs different are:

Convergence time/Calculation time
Accuracy of results
Analysis method
User friendly features
Capabilities
Number of layers which can be analyzed
Error check for accuracy of results
Seed Moduli
Software cost

Listed below are many of the backcalculation software programs that are available today *(9)*:

CHEVRON	MODCOMP	ELMOD/ELCON
BISAR	ELSDEF	EVERCALC
ELSYM5	BISDEF	WESDEF
WES5	MODCOMP3	PADAL
CHEVDEF	ISSEM4	COMDEF
MODULUS	LOADRATE	FPEDD1
ILLIPAVE	RPEDD1	WESLEA,
MICH-PAV		

3. PROGRAM SELECTION

The backcalculation programs which MoDOT evaluated in this investigation were ELMOD/ELCON, and MODULUS. When MoDOT purchased the Dynatest FWD, the backcalculation program "ELMOD/ELCON" was also purchased. This program uses the Odemark-Boussinesq Transformed Section approach employing a Poisson's ratio of 0.35 for all layers to compute the layer moduli *(10)*. The program "Modulus" was developed by a study at TTI for the Texas DOT in 1991. Version 4.0 was a revision to the original program made by TTI for the Texas DOT and uses a program WES5, a linear elastic backcalculation program, to compute standard deflection bowls based on user input *(11)*. It then uses a Hooke-Jeeves pattern search logarithm to determine the best fit of a field deflection bowl to the standard calculated deflection bowl.
A choice between programs "Elmod/Elcon" and "Modulus" had to be made. The use of both would have created extensive computer time and served no purpose but to confirm previous reports that each program was acceptable. Three test sections were selected and moduli values were computed using each program.

There were limited indications that" Modulus" provided more reasonable and consistent results, but the main reasons for the choice of "Modulus" was that it allows a review of the intermediate steps. The "MODULUS" program also produces needed information to review the acceptability and variability of the final modulus results. This information includes:

Calculated vs. field deflections
Absolute sum of errors
Convexity of bowls

Since there was not time to evaluate all of the available programs, research relied on an evaluation of backcalculation programs and procedure by SHRP. In a SHRP evaluation, the "MODULUS" Program was selected as the primary program to be used in the initial analysis of SHRP deflection data *(12)*.

4. GUIDELINES FOR USE OF BACKCALCULATION PROGRAM

The following guidelines for analysis of full depth AC pavements, full depth concrete pavements, and composite pavements (AC/PCCP) should be followed to obtain the best results with the lowest absolute sum of errors.

ANALYSIS OF FULL DEPTH AC PAVEMENTS *(9)*:

1. Accurate pavement thickness information must be obtained from historical records or representative core samples.
2. Estimate mean pavement temperature of the AC pavement from 5 day average plus pavement surface temperature. (See Appendix B)
3. From the estimated mean pavement temperature, calculate an initial estimate of the Modulus of Elasticity of the Asphalt (E_{ac}) by using the Asphalt Institute's Regression Equation. This is used to check the reasonableness of the backcalculated E_{ac} value. (See Appendix A)
4. Combine all flexible pavement layers. The E_{ac} of the various bituminous mixes, (Ex: Bituminous Base & Surface Mix), are so similar that the program can not accurately distinguish the different layers.

5. If an aggregate base is present, it may be combined with the subgrade and the pavement can be analyzed as a two layer system. This can be done when the base and the subgrade have comparable material characteristics. If a high Average Absolute Relative Difference (ABS > 2%) and/or a high Root Mean Square Error (RMS > 2.5%) is the result of combining the subgrade and base, re-analyze the pavement as a three layer system with the base as a separate layer *(9)*. (Note: Always use as few layers as possible)
6. The subgrade and/or base and subgrade combination, can be analyzed as a 36 inch layer separate from the total subgrade depth. This can be done because the first 36 inches of material under the pavement layer is the most susceptible to seasonal changes.

ANALYSIS OF FULL DEPTH CONCRETE PAVEMENTS:

1. Accurate pavement thickness information must be obtained from historical records or representative core samples.
2. If an aggregate base is present it may be combined with the subgrade and the pavement can be analyzed as a two layer system. This can be done when the base and the subgrade have comparable material characteristics. If a high Average Absolute Relative Difference (ABS > 2%) and/or a high Root Mean Square Error (RMS > 2.5%) is the result of combining the subgrade and base, re-analyze the pavement as a three layer system with the base as a separate layer *(9)*. (Note: Always use as few layers as possible)

ANALYSIS OF COMPOSITE PAVEMENTS AC/PCCP:

1. Accurate pavement thickness information must be obtained from historical records or representative core samples.

2. Estimate mean pavement temperature of the AC pavement from 5 day average plus pavement surface temperature. (See Appendix B)
3. From the estimated mean pavement temperature, calculate an initial estimate of the Modulus of Elasticity of the Asphalt (E_{ac}) by using the Asphalt Institute's Regression Equation. (See Appendix)
4. Combine all flexible pavement layers. The E_{ac} of the various bituminous mixes, (Ex: Bituminous Base & Surface Mix), are so similar that the program can not accurately distinguish the different layers.
5. If the AC layer is less than 3 inches, fix the Modulus Of Elasticity of this layer equal to the E_{ac} which was estimated by the Asphalt Institute's Regression Equation in step 3.
6. If a thin layer of AC (2 inches or less) exists beneath the PCCP, neglect the modulus of this layer and combine its thickness with the underlying layer *(13)*.
7. If an aggregate base is present, it may be combined with the subgrade and the pavement can be analyzed as a three layer system. If a high Average Absolute Relative Difference (ABS > 2%) and/or a high Root Mean Square Error (RMS > 2.5%) is the result of combining the subgrade and base, re-analyze the pavement system as a four layer system. This time combining the base and top of subgrade into a 36 inch layer separate from the rest of the subgrade. This is done to account for possible changes in the subgrade modulus with depth due to factors such as stress sensitivity of the subgrade soil, varying moisture conditions, etc. *(13)*. However, if the total subgrade thickness is less than 72 inches (due to the presence of a rigid layer) a single subgrade layer is used. (Note: Always use as few layers as possible)

Seed Moduli and Poisson's Ratio values used as input in the "MODULUS" program are depicted in the table below *(13)*.

Material Type	Modulus Range (ksi)	Poisson's Ratio
Concrete Pavement	1000 - 9000	0.15
Bituminous Pavement	200 - 3000	0.35
Cement Stabilized Base	50 - 3000	0.20
Fractured PCC Slab	50 - 3000	0.30
Asphalt Stabilized Base	10 - 1500	0.35
Lime Stabilized Base	5 - 200	0.20
Granular Base	5 - 150	0.35
Cohesionless Subgrade	5 - 100	0.35
Cohesive Subgrade	5 - 100	0.45

General rules of thumb when using backcalculation programs.

1. Use as few layers as possible to adequately define the pavement system.
2. For full depth PCC pavements a two layer system is most likely to provide the best results.
3. Avoid attempting to calculate moduli for thin layers.
4. Use seed moduli and poisson' ratio that are consistent with the pavement condition and layers.
5. Gather historical pavement data or use pavement cores to obtain accurate information on the pavement layer thickness.
6. Attempt analysis with few iterations and wide limits to identify possible solutions.
7. Evaluate the output critically before proceeding. High ABS (ABS > 2%) and RMS (RMS > 2.5%) error levels indicate that there is a problem with the analysis.

8. Subgrade moduli are critical to the rest of the analysis. Check for rigid layer depth, if the outer deflection is approximately 1 mil or less you can be reasonably sure that a stiff layer is near the surface.
9. Watch for compensating layer effects.

5. REVIEW OF MODULUS PROGRAM

The following is a list of some of the advantages of the MODULUS program.

1. Can analyze up to 4 layers of material.
2. Error check for accuracy of results.
3. Can input seed moduli and poison's ratio.
4. Low software cost.
5. Ability to efficiently analyze large FWD data files.
6. Ability to print out FWD deflections and backcalculated moduli values for each test point.
7. Allows the user to easily review the results for accuracy.

The following is a list of some of the disadvantages of the MODULUS program.

1. The program is not very user friendly.
2. The program has the ability to take an FWD data file and create a MODULUS OUT file with an .OUT extension which is used as input into the MODULUS program. MHTD personnel could not make this option work and ended up writing it's own program to create an OUT file with an .OUT extension.

(See Appendix E for examples of the MODULUS program output)

The FWD deflections and the MODULUS data were considered for use as an inventory tool, but a simpler means of depicting the structural integrity of the pavement was devised. This simpler method employs the use of defection bowl parameters, such as the deflection under the load plate, the area of the defection bowl, and the radius of curvature of the deflection bowl. These values can be stored in a data base with graphic capabilities. The pavement design engineer will then be able to graphically view the pavement's deflection bowl parameters versus the pavement's log mile location. This will allow him/her to determine which sections of pavement are structurally deficient.

REVIEW OF THE 1993 AASHTO GUIDE & DARWIN PROGRAM

The 1993 AASHTO Guide presents procedures to utilize non-destructive testing deflection data in terms of evaluating the in-situ structural capacity of pavements, evaluating joint load transfer of rigid pavements, and evaluating void detection at the joints of rigid pavement.

There are two approaches for the evaluation of in-situ structural capacity of pavements using FWD NDT deflection data. The first is the pavement layer moduli technique. The objective of this technique is to backcalculate layer moduli for each individual layer of the pavement structure. Once the layer moduli are calculated they are correlated to a layer coefficient and the effective structural capacity of the pavement can be calculated (Ex. $SN_{eff} = a_1*d_1 + a_2*d_2$). The second approach is the direct structural capacity prediction technique. In this approach the maximum deflection (at the load center) is viewed as having two parameters, the structural capacity of the pavement and the subgrade modulus. For the purpose of this report evaluation, the direct structural capacity technique will be reviewed. Detailed procedures of this technique are depicted in chapter 5 of the AASHTO Guide *(3)*.

1. DIRECT STRUCTURAL CAPACITY PREDICTION TECHNIQUE

The structural evaluation of the pavement differs depending on the pavement type. For flexible pavement the subgrade resilient modulus (M_r), effective pavement modulus (E_p), and a direct estimate of SN_{eff} of the pavement structure is calculated from derivations of Boussinesq, Boussinesq-Odemark, and a combination of Odemark and an empirical Equal Stiffness Approach equation respectively *(3 & 14)*.

For rigid pavement the effective modulus of subgrade reaction (effective k-value), the estimated modulus of elasticity of the concrete (E_{pcc}), and joint load transfer efficiency can be calculated from deflections. The effective modulus of subgrade and modulus of elasticity of the concrete are calculated from a derivation of Westergaard-Hall equations. These equations correlate the deflection under the load plate and the cross sectional area of the first 36 inches of the deflection bowl to the surface and subgrade moduli *(3)*. These in-situ values are then used to determine the required slab thickness for future traffic (D_f). The following rehabilitation techniques, that are depicted in chapter 5 of the AASHTO Guide, employ the direct structural capacity approach.

AC OVERLAY OF AC PAVEMENTS

1. Existing pavement design and construction.
   Determine thickness, material type, and subgrade soil data from construction history or coring.
2. Traffic analysis.
   Determine accumulative ESAL's in the design lane for the design life of the project (W_{18}).
3. Condition surveys.
   Define the distress types and severity.

4. Deflection testing.
   a) Calculate subgrade resilient modulus (M_R).
   b) Determine the AC mix temperature during deflection testing. This may be measured directly or estimated from 5 day average plus pavement surface temperature. The mean AC mix temperature is needed to apply the correct Temperature Adjustment Factor to the FWD d_0. The correction factor is used to adjust deflection data to a standard 68^{o} F to be consistent with the procedure of new AC pavement design.
   c) Calculate the effective pavement modulus (E_p), then use this E_p and the M_R found in step 4a to calculate a_e for checking if r is greater than or equal to $0.7a_e$.
5. Coring and material testing.
   To assess in-situ conditions of subgrade, base, and AC layers. If backcalculated results are suspect, coring and material testing will verify actual in-situ conditions.
6. Determination of required structural number for future traffic (SN_f).
   a) Design M_R is determined by applying a correction factor to the backcalculated M_R value. The correction factor is needed to correlate the backcalculated M_R to the lab M_R and to correlate to the AASHO Road Test soil which was equal to approximately 3000 psi. Recommended correction factor C = 0.33.
   b) Design present serviceability index (PSI) loss.
   c) Overlay design reliability (R%).
   d) Overall standard deviation (S_0).
   e) Use W_{18} which was determined in step 2.
   Now to compute SN_f use the above design inputs in the flexible pavement design equation or the nomograph in Part II, page II-32 Figure 3.1

7. Determine the effective structural capacity of the existing pavement (SN_{eff}).
8. Calculate structural number for overlay.

   $SN_{ol} = SN_f - SN_{eff}$
9. Calculate overlay thickness.

   $SN_{ol} = a_1 * D_{ol}$

Complete procedure is in Chapter 5 of the AASHTO Guide between pages III-95 to III-104 *(3)*. See Appendix (F) for examples of manual calculations using above procedure.

AC OVERLAY OF PCC PAVEMENTS

1. Existing pavement design.

   Existing slab thickness, type of load transfer device, and type of shoulders.
2. Traffic analysis.

   Determine accumulative ESAL's in the design lane for the design life of the project (W_{18}).
3. Condition survey

   Distress types and severity are measured and categorized as an aid to determine the effective slab thickness (D_{eff}) of the existing pavement in step 7.
4. Deflection testing.
   a) Calculate effective dynamic *k*-value. This is the dynamic bearing capacity of the subgrade and it can be determined from the stiffness response, which is the area of the deflection bowl between d_0 and d_{36}.
   b) Calculate effective static *k*-value. This is the static bearing capacity of the subgrade and it is approximately one half of the dynamic *k*-value.
   c) Calculate the modulus of PCC slab (E_{pcc}). This is determined from the dynamic *k*-value and the area of the deflection bowl between d_0 and d_{36}.
   d) Determine the percent of joint load transfer (LT%). This is used to estimate the joint load transfer value (J).

5. Coring and materials testing.
   To assess in-situ conditions of subgrade, base, and PCC layers. If backcalculated results are suspect, coring and material testing will verify actual in-situ conditions.
6. Determine required slab thickness for future traffic (D_f).
   a) Use effective static *k*-value which was determined in step 4b.
   b) Design present serviceability index (PSI) loss.
   c) Use joint load transfer (J) which was determined in step 4d.
   d) Calculate PCC modulus of rupture of the existing slab (S'_c). This can be estimated from the backcalculated E_{pcc}.
   e) Use E_{pcc} as determined in step 4c.
   f) Determine loss of support of existing slab (LS). Joint corners that have loss of support may be identified by using FWD deflection testing as described in Chapter 3 (3.5.5 Use in Slab Void Detection) of the AASHTO Guide. For overlay thickness design assume a fully supported slab, LS=0.
   g) Overlay design reliability (R%).
   H) Overall standard deviation (S_0).
   I) Determine subdrainage capability of the existing slab. In selecting this value, note that the poor subdrainage situation at the AASHO Road Test would be given a Coefficient of Drainage C_d=1.

   J) Use estimated accumulative ESALs in the design lane for the design life of the project (W_{18}) which was found in step 2.
   Now to compute D_f use the above design inputs in the rigid pavement design equation or the nomograph in Part II, pages II-45 & II-46 Figure 3.7

7. Determine effective slab thickness (D_{eff}) of existing pavement. The information obtained from the condition survey, which was performed in step 3, is used here to determine the adjustment factors needed to reduce the existing slab thickness to the effective slab thickness.
   a) Joint and crack adjustment factor (F_{jc}).
   b) Durability adjustment factor (F_{dur}).
   c) Fatigue damage adjustment factor (F_{fat}).
   d) Determine D_{eff}.

      $D_{eff} = F_{jc} * F_{dur} * F_{fat} * D$
8. Determine overlay thickness (D_{ol}).

   $$D_{ol} = A*(D_f - D_{eff})$$

   Where A is a factor to convert PCCP thickness deficiencies to AC overlay thickness.

   $$A = 2.2233 + 0.0099(D_f - D_{eff})^2 - 0.1534(D_f - D_{eff})$$

Complete procedure is in Chapter 5 of the AASHTO Guide between pages III-115 to III-125 *(3)*. See Appendix (F) for examples of manual calculations using above procedure.

AC OVERLAY OF AC/PCC PAVEMENTS

1. Existing pavement design.
   Existing AC thickness, existing PCCP slab thickness, type of load transfer in the PCCP slab, and type of shoulders.
2. Traffic analysis.
   Determine accumulative ESALs in the design lane for the design life of the project (W_{18}).
3. Condition survey.
   Distress types and severity are measured and categorized as an aid to determine the effective slab thickness (D_{eff}) of the existing pavement in step 7.
4. Deflection testing.
   a) Temperature of the AC mix. The mean temperature of the AC pavement layer may be obtained by either direct measurement or by estimation. The AC temperature is needed to estimate the E_{ac} and compression of the AC layer during the time of testing.
   b) Elastic modulus of AC. The elastic modulus of the AC (E_{ac}) may be determined from the estimated AC temperature and the Asphalt Institute's Regression Equation or by diametral resilient modulus testing of AC cores in the lab.
   c) Effective dynamic *k*-value beneath PCCP slab. First the compression of the AC layer is calculated and subtracted from the total FWD d_0. The remaining deflection is caused by the PCCP slab and the subgrade. The dynamic *k*-value is then determined from the $Area_{pcc}$ of the deflection bowl between d_0 and d_{36} which was caused by the PCC and subgrade.
   d) Effective static *k*-value. Calculate effective static *k*-value. This is the static bearing capacity of the subgrade and it is approximately one half of the dynamic *k*-value.

e) Elastic modulus of PCCP slab (E_{pcc}). Calculate the modulus of PCCP slab (E_{pcc}). This is determined from the dynamic *k*-value and the $Area_{pcc}$ of the deflection bowl between d_0 and d_{36}.

f) Joint load transfer. Determine the percent of joint load transfer (LT%). This is used to estimate the joint load transfer value (J).

5. Coring and material testing.

To assess in-situ conditions of subgrade, base, and PCC layers. If backcalculated results are suspect, coring and material testing will verify actual in-situ conditions.

6. Determine required slab thickness for future traffic (D_f).

a) Use effective static *k*-value which was determined in step 4d.

b) Design present serviceability index (PSI) loss.

c) Use joint load transfer (J) which was determined in step 4f.

d) Calculate PCC modulus of rupture of the existing slab (S'_c). This can be estimated from the backcalculated E_{pcc}.

e) Use E_{pcc} as determined in step 4e.

f) Determine loss of support of existing slab (LS). Joint corners that have loss of support may be identified by using FWD deflection testing as described in Chapter 3 (3.5.5 Use in Slab Void Detection) of the ASSHTO Guide. For overlay thickness design assume a fully supported slab, LS=0.

g) Overlay design reliability (R%).

h) Overall standard deviation (S_0).

i) Determine subdrainage capability of the existing slab. In selecting this value, note that the poor subdrainage situation at the AASHO Road Test would be given a was Coefficient of Drainage C_d=1.

j) Use estimated accumulative ESALs in the design lane for the design life of the project (W_{18}) which was found in step 2.

Now to compute D_f use the above design inputs in the rigid pavement design equation or the nomograph in Part II, pages II-45 & II-46 Figure 3.7

7. Determine effective slab thickness (D_{eff}) of existing pavement. The information obtained from the condition survey, which was performed in step 3, is used here to determine the adjustment factors needed to reduce the existing slab thickness to the effective slab thickness.
   a) Joint and crack adjustment factor (F_{jc}).
   b) Durability adjustment factor (F_{dur}).
   c) AC quality adjustment factor (F_{ac}).
   d) Determine D_{eff}.

   $$D_{eff} = (D_{pcc} * F_{jc} * F_{dur}) + ((D_{ac}/2) * F_{ac})$$

8. Determine overlay thickness (D_{ol}).

$$D_{ol} = A*(D_f-D_{eff})$$

Where A is a factor to convert PCC thickness deficiencies to AC overlay thickness.

$$A = 2.2233 + 0.0099(D_f-D_{eff})^2 - 0.1534(D_f-D_{eff})$$

Complete procedure is in Chapter 5 of the AASHTO Guide between pages III-128 to III-135 *(3)*. See Appendix (F) for examples of manual calculations using above procedure.

2. REVIEW OF THE DARWin PROGRAM

The DARWin Pavement Design System program was developed for AASHTO by ERES Consultants Inc. of Savoy, Illinois. The only portion of the program that was used for this report was the Overlay Design Procedure. The Overlay Design Procedure employs NDT deflections as an alternate method to calculate overlay thickness. This portion of the program, as with all other parts of the program, employs the design procedures and equations that are found in the 1993 AASHTO Design Guide. To use the overlay design procedure, follow the sequence listed below (7).

1. Select the type of overlay to be designed.
2. Select structural capacity for future traffic.
3. Input future 18-kip ESALs over design period, initial serviceability, terminal serviceability, reliability level, and overall standard deviation. These values are for AC overlay of AC pavement, for AC overlay of PCC pavement or AC overlay of AC/PCC the user must also input joint load transfer and overall coefficient of drainage.
4. Backcalculate material moduli values using FWD deflection data. A choice is available to use either point-by-point or a uniform section procedure.
5. Apply seasonal correction to subgrade resilient modulus or static *k*-value if FWD deflection data for different seasons is available.
6. Estimate joint load transfer for existing PCC or AC/PCC pavements by calculating point-by-point or uniform section deflection load transfer efficiency.
7. Determine the effective structural capacity of the existing pavement. For AC overlay of AC pavements three options are given: component analysis method, remaining life method, and NDT method. For AC overlay of PCC pavements two options are available: condition survey method and remaining life method. For AC overlay of

AC/PCC pavements the only method available is the condition survey.

8. Determine the overlay structural capacity by using the calculated future and effective structural capacities. The user may use any or all of the available existing pavement evaluation methods.
9. Select specified layer design, optimized layer design, or overlay layer information, depending on the type of overlay, to determine the overlay design thickness.

Complete procedure is in the DARWin Pavement Design System User's Guide (7). See Appendix (F) for examples of DARWin output using the above procedure.

As with all programs there are associated advantages and disadvantages (7).

The advantages of the program are as follows:

a) User friendly
b) Technically accurate
c) Ability to accept FWD data collection files
d) Ability to provide point-by-point or uniform section analysis of FWD NDT deflection data.
e) Can calculate, display, and print all of the overlay design factors associated with the FWD NDT deflections and backcalculation. For flexible pavements these values are the Resilient modulus (M_R), Effective Pavement Modulus (E_p), Effective Structural Number of existing pavement (SN_{eff}), Required Structural Number for future traffic (SN_f), and Depth of Overlay (D_{ol}). For rigid pavements these values are the Effective Static *k*, Modulus of Elasticity of the existing PCC slab (E_{pcc}), Modulus of Rupture of the existing PCC slab (S'_c), Joint Load Transfer (LT%), Required Slab Thickness for Future Traffic (D_f), and Depth of Overlay (D_{ol}).

f) Ability to calculate Effective Resilient Modulus (M_{Reff}) and Effective Modulus Of Subgrade Reaction (k_{eff}). These soil bearing capacity values take into account the seasonal variations in the subgrade conditions. These procedures are on pages II-12 to II-16 and II-37 to II-44 of the 1993 AASHTO Design Guide.
g) Ability to calculate joint load transfer efficiencies either by uniform section or point-by-point analysis.
h) An excellent tool for analyzing pavement at a project level.

The disadvantages of the program are as follows:

a) In the point-by-point process deflection data must be entered manually for each particular test point, consequentially disabling the program in its capability to be used at an inventory level.
b) The uniform section procedure allows analysis of an entire FWD data collection file. The file name is entered as input and then the program backcalculates the average moduli, calculates the average structural capacity, and calculates average overlay thickness. The advantage of this process is that the program has the ability to accept FWD data files and make all of the needed calculations without manual input of each test point. This works well as long as the test points in the file are fairly uniform. If the file contains multiple sections of different uniformity that will require variable overlay thickness, the average of the sections will produce an inferior overlay in the weaker section and an over designed overlay in the stronger section.

c) The program was found to be accurate in estimating the in-situ structural capacity of full depth rigid or flexible pavements, but is sometimes inaccurate when estimating the structural capacity of composite pavements (AC/PCCP). The program, as well as the equations it was based on, do not accurately estimate the amount of deflection/compression which is contributed by each layer of the composite pavement.

A problem lies with the program's inability to provide and print a graphical representation of the test point locations, represented on the x-axis as stationing or log miles, versus the FWD D_0, subgrade bearing capacity (M_R) or static *k*-value, and/or effective structural capacity, on the y-axis. This would allow the user to determine where the uniform sections are within an FWD data file. Another problem is that the program does not have the ability to analyze a particular section within an FWD data file. That is, the user can not analyze a pavement between the station limits which make up the uniform section. The program can only analyze the whole file.
This also disables the program in its use at the inventory level.

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STRUCTURAL CAPACITY OF IN SERVICE PAVEMENTS

1. Comparison Of Modulus And DARWin Results

Calculating the structural capacity of in-service pavements and the rehabilitative overlay thickness to correct structural deficiencies can be accomplished by using the design equations in Chapter Five of the AASHTO Design Guide. The "DARWin" program utilizes these design equations and is a quick and efficient way to accomplish this task. The DARWin program can be used effectively at the project level but is inadequate at the inventory level.

The "Modulus" program has the ability to backcalculate moduli layers, which can provide an indication of the pavement's structural capacity, but does not have the ability to calculate the structural capacity or rehabilitative overlay thickness. The Modulus program is a good quantitative tool, but is inadequate at an inventory and project level.

From investigating the use of deflection results, the question arose if the backcalculated Modulus program values could be employed in the AASHTO design equations, and if so, would the resulting structural capacities and overlay thickness be comparable to that generated by the AASHTO design equations and the DARWin program? If the results are comparable, there is then a correlation which may allow the Modulus program to be used at the inventory level to depict structurally deficient areas of roadway. The DARWin program could then be used at the project level to accurately calculate the structural capacity and overlay thickness for the area of roadway which was found to be deficient.

With this thought in mind the researcher decided to calculate the structural capacity and required rehabilitative overlay thickness manually with the AASHTO Design equation's, with the computer using the DARWin program, and by using the Modulus program backcalculated moduli layer values in the AASHTO Design equations. The purpose of the manual calculations was to review the AASHTO Design equations and familiarize the researcher with the equations derivations and input variables. The use of the DARWin program allowed the researcher to review the program's capabilities and user friendliness. This program uses the 1993 AASHTO Design Equations in Chapter 5 of the guide. From these two calculations a comparison and confirmation of the manual results to the computer generated results could be made. The purpose of the third procedure was to see if backcalculated layer moduli values could be used in the AASHTO Design equations. The researcher realized that different layer moduli values would be obtained from the different procedures.

Three different types of pavement structures were evaluated for their existing structural capacity and required AC overlay. The first type was full depth AC pavements, the second type was an existing AC overlay of PCCP, and the third type was full depth PCC pavements.

In the full depth AC pavement analysis, where the Modulus program backcalculated layer moduli values were used in the AASHTO Design equations, two variations on how to calculate the Effective Structural Number (SN_{eff}) for the AC pavements were employed. The first way was to backcalculate the layer moduli for each separate layer of the pavement structure. This was accomplished by entering into the Modulus program the corresponding thickness, poisson's ratio, and seed moduli range of values for each layer. In the design analysis for AC overlay of AC pavements, D=depth of AC plus base thickness and the Effective Pavement Modulus (E_p) is the modulus of the AC and base combined. Since layer moduli were calculated for each individual layer the researcher let the backcalculated $E_{ac}=E_p$ and $D=D_{ac}$. The second way was to combine the AC and base thickness into one layer, letting D=D and $E_p=E_p$, then directly solve for the value of E_p.

In each means of analysis the first 36 inches of the subgrade was analyzed as a separate layer. This approach to analyzing the subgrade can be employed because the first 36 inches of the subgrade is the most susceptible to environmental effects which seasonally alter its characteristics. By analyzing the subgrade in this fashion the researcher found the lowest backcalculation error values, which is the best fit between the actual deflection bowl and the theoretical deflection bowl. In this type of subgrade analysis, if the depth to stiff layer is less than 10 feet, the Resilient Modulus (M_r) is equal to the value determined for the first 36 inches. If the depth to the stiff layer is greater than 10 feet then the M_r value is the average of the first 36 inch value and the remaining depth of subgrade value.

The results show that the first method of analysis depicts an effective structural capacity and overlay thickness which best correlates to that which was calculated from using the deflections in the AASHTO Design equations and DARWin program. (See Appendix G for results). These limited results show that the Modulus Program backcalculated layer moduli value differ from the moduli values which were backcalculated from the AASHTO Design equations. But, even though the layer moduli values differ, the ending overlay thickness is reasonably comparable.

Since one of the inabilities of the Modulus program is its ability to accurately backcalculate thin layers, the researcher deduced that the strength of materials characteristic of the 4 inch aggregate base layer was inaccurate.

It seems that through compensating layer effects, the Modulus Program allotted higher than expected values to the AC layer modulus and the subgrade resilient modulus. These higher than expected values came from the strength of the base layer, which the program gave a lower than expected value.

In the analysis of AC/PCC pavements and full depth PCC pavements, where the backcalculated Modulus program values were used in the AASHTO Design equations, the Modulus program Resilient Modulus (M_r) value had to be converted to a Bearing Capacity static k-value. This was accomplished by first multiplying this dynamic M_r value by 0.33 to give the resulting Design M_r. The Design M_r was then divided by 19.4 to produce an estimated static k-value *(3)*. (See Appendix G for results)

Again a comparison was made with the results obtained from using the FWD deflections in the AASHTO design equations and DARWin program, to the results obtained from using the Modulus program backcalculated layer moduli values in the AASHTO design equations. (See Appendix G for results). The results again show overlay thickness which are reasonably comparable. The future depth thickness (D_f), which is indicative of the structural capacity of AC/PCC and PCC pavements, is also reasonably comparable.

Therefore since they are reasonably comparable, the Modulus program values could be used in the DARWin program to more accurate estimate the structural capacity of composite pavements.

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TENTATIVE IMPLEMENTATION OF SUBSEQUENT KNOWLEDGE

1. INVENTORY & PROJECT LEVEL

As an inventory tool, the deflection data from the FWD can be used in a data base program which should be designed to calculate key deflection bowl parameters. Such deflection bowl parameters as; the deflection under the load plate, the area of the deflection bowl, and the radius of curvature of the deflection bowl should be incorporated into this data base program. This data base should have graphical capabilities which will enable the user to graphically display these key structural indicators versus log mile or station of roadway. (See Appendix H for example of graphical representation)

A data base file of this type could be incorporated into the Pavement Management System (PMS). This structural information when coupled with serviceability information, such as International Roughness Index, Skid Resistance, Distress Index, etc., will allow the pavement design engineer to see if the roadway has structural deficiencies, functional deficiencies, and/or both. This will provide the pavement design engineer a tool for determining the most appropriate rehabilitation process for the pavement. This will lead to a more effective use of resources. Also, this type of data base, when updated on a systematic schedule over an extended period of time, can depict a pavement's performance and deterioration curve. This may also lead to pavement performance modeling and the subsequent prediction of the next rehabilitative measure.

From this graphical representation, the pavement design engineer can identify uniform areas of structural deficiencies. Once these areas are located, the FWD file containing this information can then be used in the DARWin program to calculate the structural capacity and needed overlay thickness for rehabilitation.

2. SHORTCOMINGS OF THE IMPLEMENTATION ENDEAVOR

If the DARWin program had the capability to calculate and graphically plot, for each test location, the structural elements of a pavement (such as D_0, M_r, E_p, and SN_{eff} for full depth AC pavements and K_{stat}, E_{pcc}, D_f, and LT% for PCC and AC/PCC pavements) versus log mile or station, and then print this information to a file, it could be extracted and exported to a data base in the PMS. If it also had the capability to evaluate specific sections of an FWD data file (once a uniform section of structural deficiency is located from the graphical analysis, the limits of the deficiency can be analyzed separate from the rest of the FWD file) most of the inadequacies of implementation would be solved.

The researcher opted to use the DARWin program as an example because it is a good program, it follows Chapter 5 of the AASHTO Design Guide, and is an excellent tool at the project level. But if the above mentioned inadequacies were corrected, this program would also make a excellent tool at the inventory level.

At the present time tentative implementation procedures should start with the design of the before mentioned data base for use at the inventory level and the DARWin program at the project level. Some of the shortcomings which need to be overcome are listed below:

Set up a data base with graphical capabilities which could ultimately be incorporated into a Pavement Management System.

The data base program should incorporate a scanning procedure which will allow the pavement design engineer to scan large segments of pavement. This scanning should be set up to detect structurally deficient segments of pavement.

Write a program which can calculate the percent of load transfer (LT%) of PCCP joints and export results to the data base.

Once a uniform section of structural deficiency is located from the graphical analysis and scanning procedure, a program will be needed to extract from an FWD file the limits of the uniform section. This is needed so this uniform section can be analyzed by the DARWin program.

At this time these tasks are incomplete. They will be tedious and time consuming but well worth the effort. The researcher needs to constantly review the latest innovations in the area of implementing the use of FWD deflection data at the inventory level. From this review a better means of implementation may arise. Until then this implementation procedure will be pursued.

CONCLUSIONS

1. The Falling Weight Deflectometer(FWD) is best suited for MoDOT's needs in determining the structural condition of in-service pavements from Non-Destructive Testing (NDT) deflections.

2. The use of the FWD to evaluate the changing structural condition of test sections is a valuable tool in the continued research of differing pavement types and rehabilitative construction techniques.

3. The use of the FWD and the determination of the needed values from testing are not completely standardized.

4. The backcalculation of the moduli values of pavement layers can be accomplished with the program "Modulus".

5. A data base program should be constructed to calculate and store key deflection bowl parameters. These key deflection bowl parameters should include the deflection under the load plate, the area of the deflection bowl, and the radius of curvature of the deflection bowl. This data base should have graphical capabilities which will allow the pavement design engineer to graphically display these key deflection bowl parameters versus the log mile of the pavement. This data base should also have a scanning mechanism which will allow the pavement design engineer to scan large segments of pavement for structurally deficient sections. This data base should be structured so it can be inevitably incorporated into a Pavement Management System (PMS).

6. The effective structural capacity of the pavement can be estimated using the 1993 AASHTO Pavement Design Guide and the pavement design program "DARWin". The DARWin program can be used to analyze pavements at and to calculate a required rehabilitative overlay thickness at the project level. One word of caution; the program, as well as the equations it is based on, sometimes yield erroneous result in the analysis of composite pavements (AC/PCCP). This is due to the amount of deflection/compression which assigned to the PCCP and the AC layer.

7. MoDOT should not consider this topic completely evaluated. There are daily changes in Non-Destructive Testing (NDT) equipment and the processes that use the FWD's output. Further improvements on mechanistic-empirical analysis and design from NDT data is inevitable. And, a simpler means to incorporate NDT results into a PMS system will surely be innovated.

8. Since its infancy, the FWD and the backcalculation process/procedures have evolved to the point where usable information on the structural capacity of in-service pavements can be obtained.

RECOMMENDATIONS

1. MoDOT should institute a testing program with the FWD that would provide both a combination of inventory and project level information. The interstate and primary routes should all be tested and the data inventoried into a data base with graphical capabilities.

2. This testing program should be on a two year interval and conducted as outlined in this report.

3. The use of the FWD and the computation of the needed output from the FWD should remain in the control of someone familiar with the entire process and its shortcomings.

4. MoDOT should continue to use the Dynatest FWD to promote data uniformity and staff familiarity with the equipment and its expected results.

5. MoDOT should establish its own absolute calibration center if more FWD units are purchased.

6. MoDOT should continually review changes in this field and use any collected information, internal or external, to update the proposed process.

At the present time tentative implementation procedures should start with the design of the before mentioned data base for use at the inventory level and the DARWin program at the project level. Some of the shortcomings which need to be overcome are listed below:

Set up a data base with graphical capabilities which could ultimately be incorporated into a Pavement Management System.

The data base program should incorporate a scanning procedure which will allow the pavement design engineer to scan large segments of pavement. This scanning should be set up to detect structurally deficient segments of pavement.

Write a program which can calculate the percent of load transfer (LT%) of PCCP joints and export results to the data base.

Once a uniform section of structural deficiency is located from the graphical analysis and scanning procedure, a program will be needed to extract from an FWD file the limits of the uniform section. This is needed so this uniform section can be analyzed by the DARWin program.

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Appendices

A. Graph of E_{ac} versus Asphalt Temperature which was plotted using average MoDOT mix values and the Asphalt Institutes Regression Equation.

B. Graphs and regression equations to estimate mean AC mix temperature from the past 5 day average air temperature plus the present pavement surface temperature. Graphs were constructed from MoDOT pavement data following H.F. Southgate's procedure (*6*).

C. Graph of AC temperature versus AC layer compression.

D. Example of backcalculation using Boussinesq & Odemark's equations.

E. Examples of MODULUS program output.

F. Examples of manual calculations to determine overlay thickness using NDT deflection data and the Chapter 5 AASHTO Design Guide and the accompanying DARWin program results.

G. Comparison of MODULUS backcalculated data, manual backcalculated data from following Chapter 5 AASHTO Design Guide procedure, and DARWin program data.

H. Example of graphical representation of the pavements structural elements verses log mile or station.

APPENDIX A

From the Asphalt Institute Regression Equation, the modulus of elasticity of an asphalt mix can be estimated from the mix properties and mix temperature. This equation was employed by inserting MoDOT average mix property values into the equation. The temperature was then varied between 30 and 120 degrees F at 5 degree increments. These values were plotted to form a graph of AC Modulus Of Elasticity versus AC Mix Temperature.

As part of the NDT data collection procedure, the ambient air temperature, pavement surface temperature, and previous past 5 days average temperature are recorded. From this information the mix temperature of the asphalt can be estimated. And from the estimated mix temperature the estimated modulus of elasticity of the AC can be obtained from the graph.

From this, the researcher and/or pavement engineer has a general ideal of what the backcalculated modulus of elasticity of the AC pavement should be. Note that this is just a ball park figure because the backcalculated results will differ depending on how the particular backcalculation program assigns its strengths to the layers. But this is a good way to check the backcalculated output, because the results are usually in a general proximity of each other. If the results are not similar, this indicates either bad temperature information or bad thickness information on the AC pavement.

Below is the Asphalt Institute Equation and a list of the MHTD mix properties used.

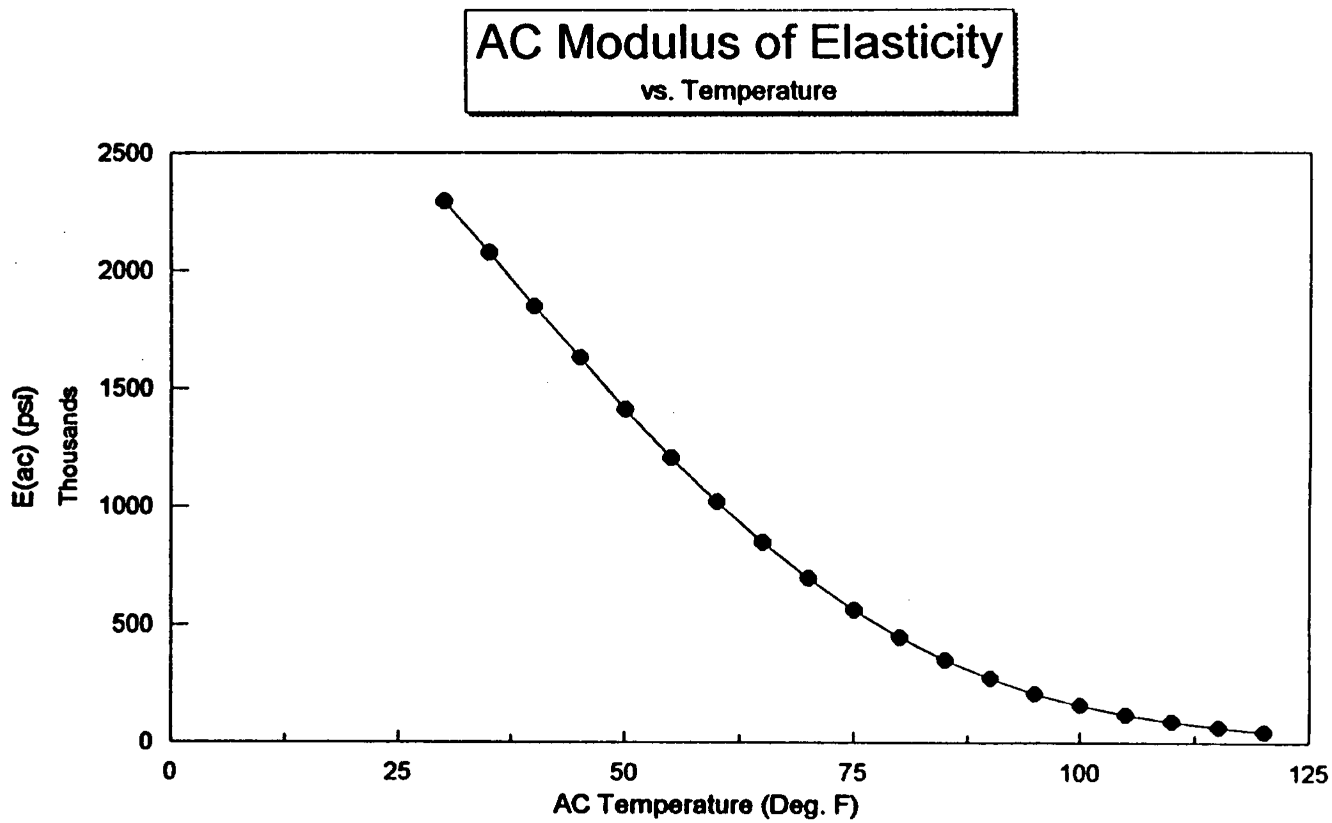
$$\log E_{ac} = 5.553833 + 0.028829\left(\frac{P_{200}}{F^{0.17033}}\right) - 0.03476V_v$$
$$+0.070377n_{70\,\text{degrees}\,F,10^6} + 0.000005t_p^{(1.3+0.49825\log F)}P_{ac}^{0.5}$$
$$+0.931757\left(\frac{1}{F^{0.02774}}\right)$$

where:
E_{ac} = elastic modulus of AC, psi (unknown)
P_{200} = percent aggregate passing the No. 200 sieve (MHTD = 6%)
F = loading frequency (MHTD = 18 Hz)
V_v = air voids, percent (MHTD = 5%)
$n_{70degrees,10^6}$ = absolute viscosity at 70 degrees F, 10^6 poise (MHTD = 2)
P_{ac} = asphalt content, percent by weight of mix (MHTD = 6%)
t_p = AC mix temperature, degrees F (varied)

After inserting the MHTD average mix properties, the resulting equation is as follows:

$$\log|E| = 6.486476 - 1.8038865*10^{-4}*t_p^{1.92544}$$

t(p) (deg. F)	E(ac) (psi)
30	2.293E+06
35	2.075E+06
40	1.850E+06
45	1.627E+06
50	1.411E+06
55	1.207E+06
60	1.018E+06
65	8.476E+05
70	6.959E+05
75	5.637E+05
80	4.506E+05
85	3.554E+05
90	2.766E+05
95	2.124E+05
100	1.610E+05
105	1.204E+05
110	8.893E+04
115	6.482E+04
120	4.663E+04



APPENDIX B

In the AASHTO Design Guide, one of the suggested means to estimate the AC pavement temperature is from the pavement surface temperature plus previous 5 day average air temperature which was developed by Southgate. As part of an ongoing MoDOT study, Research Investigation RI91-09A "Temperature Adjustment Factors For Falling Weight Deflectometer Deflections On Full Depth Asphalt Concrete Pavements", Southgate's methodology was followed to create AC pavement temperature estimations for MoDOT pavements. By using temperature information that had been collected from SPS-6 and 9 Monthly testing sites, the researchers wanted to see if Southgate's results were reproducible.

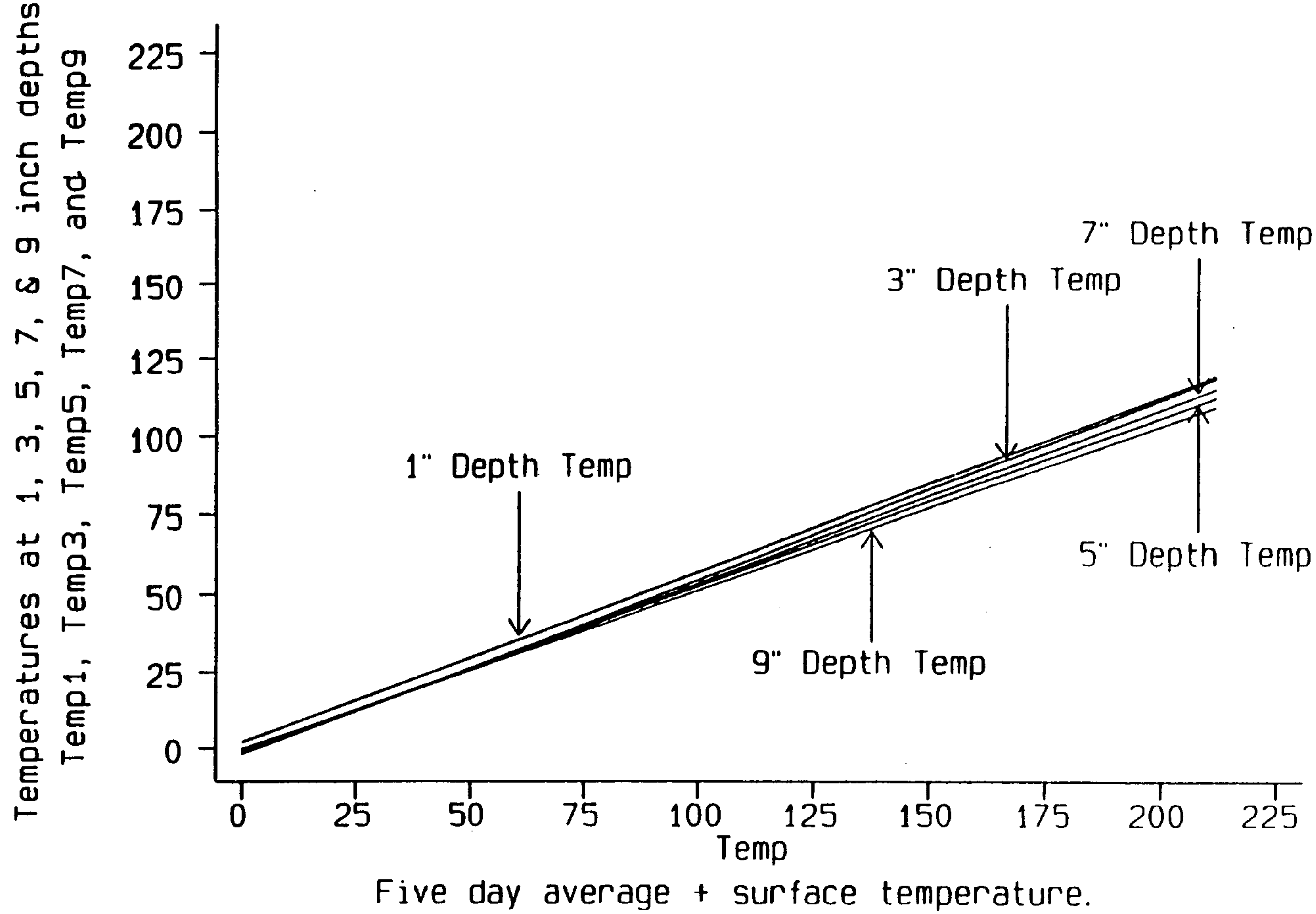
Our research came up with good results. The following regression equations and graphs can be used to estimate the AC pavement temperature. The researcher is satisfied that Southgate's methodology is valid and reproducible. One of the FWD data collection programs employs Southgate's regression equations to calculate the AC mix temperature. Therefore, the FWD data collection program which employs Southgate's regression equation will be used at this time. There is ongoing research by other organizations in this same area which could produce even a better means to estimate AC mix temperature.

Regression values for 5 day average + surface temperature vs. depth temperature
(Asphalt pavement temperatures.)
Estimated linear regression equation: $Y\hat{} = m*X + b$
X = 5 Day average + surface temperature
Y = Depth temperature

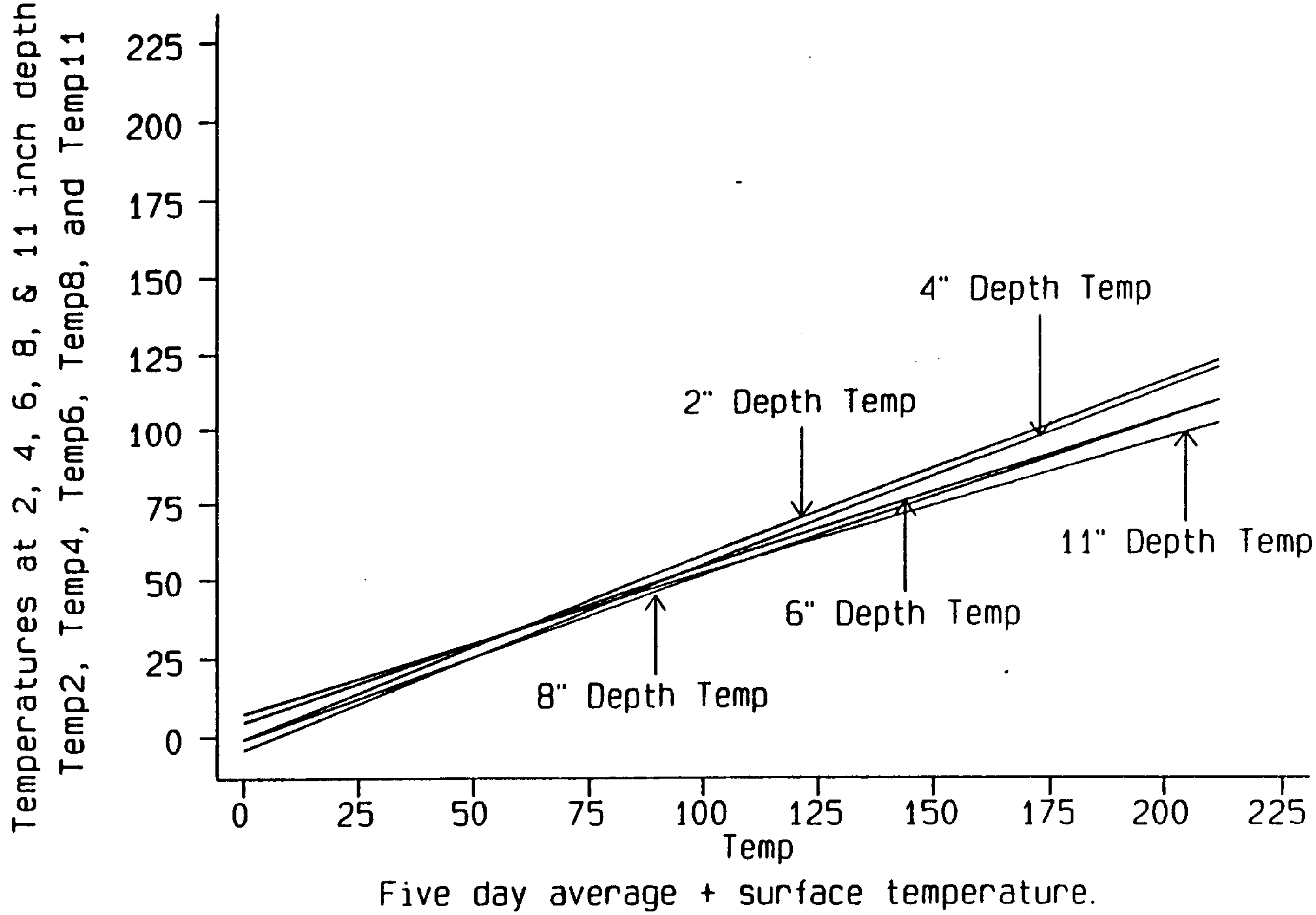
Variable:	Sample Size n:	F–value:	Prob. > F:	Significant (Y/N):	Rsquare:	Mean Sq. Error MSE:	SqRt(MSE) S(y.x):
Temp1	30	242.68	0	Y	0.8966	57.95516	7.612829
Temp2	132	1267.5	0	Y	0.907	30.62344	5.533845
Temp3	56	163.22	0	Y	0.7514	40.06890	6.330000
Temp4	125	947.5	0	Y	0.8851	28.48441	5.337078
Temp5	32	683.99	0	Y	0.958	14.97158	3.869313
Temp6	31	414.9	0	Y	0.9347	17.90409	4.231323
Temp7	98	962.84	0	Y	0.9093	21.13139	4.596889
Temp8	27	139.09	0	Y	0.8476	16.31185	4.038794
Temp9	12	170.74	0	Y	0.9447	25.42144	5.041968
Temp11	13	18.01	0.0014	Y	0.6208	13.68139	3.698836

Variable:	b Y–int.:	m Slope:	Std. Err. Coeff.(m):	T–value:	Prob. > T:	Significant (Y/N):
Temp1	2.151643	0.548537	0.035211	15.57827	0	Y
Temp2	−0.48153	0.577301	0.016215	35.60181	0	Y
Temp3	−1.88034	0.563716	0.044124	12.77571	0	Y
emp4	−4.02543	0.582710	0.018930	30.78141	0	Y
Temp5	−0.36269	0.528364	0.020202	26.15316	0	Y
Temp6	4.724505	0.490000	0.024056	20.36915	0	Y
Temp7	−1.22778	0.545164	0.017569	31.02954	0	Y
Temp8	−0.63232	0.514906	0.043659	11.79378	0	Y
Temp9	−0.16731	0.513581	0.039304	13.06674	0	Y
Temp11	7.420474	0.441511	0.104030	4.244042	0.001	Y

Regression lines for five day average + surface temperature versus temperatures at 1, 3, 5, 7, & 9 inch depths.



Regression lines for five day average + surface temperature versus temperatures at 2, 4, 6, 8, & 11 inch depths.



APPENDIX C

The method used to calculate the amount of asphalt concrete compression was based on Boussinesq's one layer system as well as on the theory of equivalent thickness presented by Odemark. Initially, Boussinesq's one layer system alone was used to find deflections. In 1885, Boussinesq developed a solution for computing stresses and deflections in a halfspace (soil) composed of homogeneous, isotropic and linearly elastic material. This solution was based on a point loading, and in 1928, Love adapted his solution for a circular load. *(5)* The equation below is for deflection at depth z:

$$d_z = \frac{(1+u)pa}{E}\left\{\frac{1}{\sqrt{1+\left(\frac{z}{a}\right)^2}} + (1-2u)\left(\sqrt{1+\left(\frac{z}{a}\right)^2} - \frac{z}{a}\right)\right\}$$

where:

p = plate pressure (ksi)

E = elastic modulus (ksi)

a = plate radius (inches)

z = depth below pavement surface (inches)

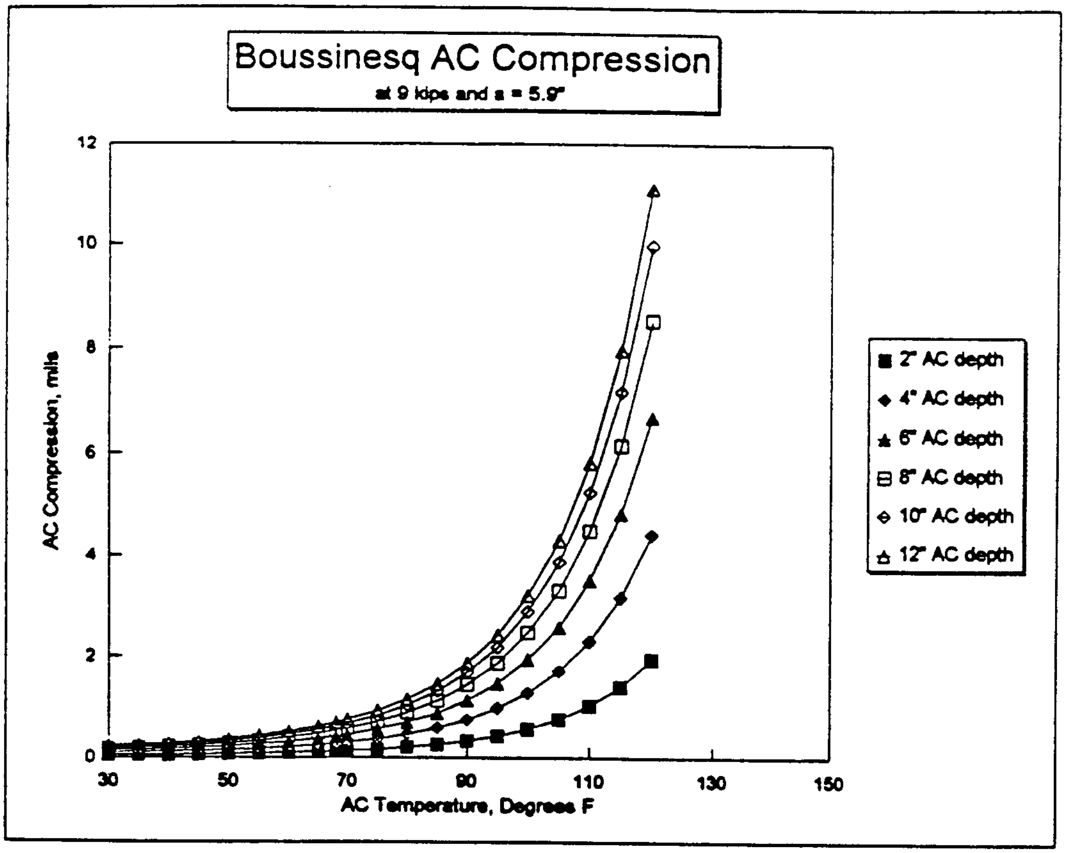
u = Poisson's ratio

This method shows the theoretical amount of compression the AC layer is subjected to due to different AC temperatures and layer depths. As can be seen in the table and graph on the next page, it is an exponential curve and at the +/- 85 degrees Fahrenheit range, the amount of compression becomes greater and greater. Therefore, once the estimated mix temperature becomes greater than 85 degrees Fahreneheit, the AC mix temperatures should be taken manually.

This is especially applicable to testing on AC/PCC pavements. When the AASHTO Design Guide (Chapter 5) discusses the rehabilitation of AC/PCC pavements, it states that the compression of the AC layer is estimated and subtracted from the D(0) total, resulting in the remaining deflection cause by the PCCP.

$$D_{0_{TOTAL}} = D_{0_{AC\ COMPRESSION}} + D_{0_{PCCP\ DEFLECTION}}$$

The accuracy of the estimated E(ac) is then pertinent to the resulting E(pcc) value.



Bousinessq Method
for Center of Plate AC Compression

		AC Compression at Depth					
t(p) (deg. F)	E(ac) (psi)	2 inches (mils)	4 inches (mils)	6 inches (mils)	8 inches (mils)	10 inches (mils)	12 inches (mils)
0	3.065E+06	0.0295	0.0670	0.1018	0.1300	0.1518	0.1687
5	3.037E+06	0.0298	0.0676	0.1027	0.1312	0.1532	0.1703
10	2.960E+06	0.0305	0.0694	0.1054	0.1346	0.1572	0.1747
15	2.840E+06	0.0318	0.0723	0.1099	0.1403	0.1639	0.1821
20	2.684E+06	0.0337	0.0765	0.1163	0.1485	0.1734	0.1927
25	2.499E+06	0.0362	0.0822	0.1249	0.1594	0.1862	0.2070
30	2.293E+06	0.0394	0.0895	0.1361	0.1737	0.2029	0.2255
35	2.075E+06	0.0436	0.0990	0.1504	0.1920	0.2243	0.2493
40	1.850E+06	0.0488	0.1110	0.1687	0.2153	0.2515	0.2795
45	1.627E+06	0.0555	0.1262	0.1918	0.2448	0.2860	0.3178
50	1.411E+06	0.0640	0.1455	0.2211	0.2823	0.3298	0.3665
55	1.207E+06	0.0749	0.1701	0.2585	0.3301	0.3855	0.4285
60	1.018E+06	0.0887	0.2016	0.3064	0.3912	0.4570	0.5079
65	8.476E+05	0.1066	0.2423	0.3682	0.4701	0.5491	0.6102
68	7.542E+05	0.1198	0.2722	0.4138	0.5282	0.6170	0.6858
70	6.959E+05	0.1299	0.2951	0.4484	0.5725	0.6687	0.7432
75	5.637E+05	0.1603	0.3642	0.5536	0.7068	0.8255	0.9175
80	4.506E+05	0.2006	0.4557	0.6926	0.8843	1.0329	1.1479
85	3.554E+05	0.2543	0.5778	0.8782	1.1212	1.3096	1.4555
90	2.766E+05	0.3268	0.7424	1.1284	1.4406	1.6828	1.8702
95	2.124E+05	0.4255	0.9667	1.4692	1.8757	2.1910	2.4350
100	1.610E+05	0.5613	1.2753	1.9383	2.4746	2.8906	3.2125
105	1.204E+05	0.7503	1.7048	2.5910	3.3079	3.8639	4.2942
110	8.893E+04	1.0162	2.3088	3.5090	4.4800	5.2329	5.8157
115	6.482E+04	1.3942	3.1679	4.8147	6.1469	7.1800	7.9796
120	4.663E+04	1.9380	4.4034	6.6925	8.5443	9.9803	11.0919
125	3.311E+04	2.7290	6.2006	9.4240	12.0316	14.0537	15.6189
130	2.322E+04	3.8928	8.8447	13.4427	17.1623	20.0466	22.2793
135	1.607E+04	5.6247	12.7799	19.4236	24.7980	28.9657	32.1917

Appendix D depicts the use of Boussinesq's point load equation and Odemarks transformed section equation. These two equations are the very basics of static mechanistic backcalculation

APPENDIX D

Equivalent Thickness Transformation, different Poisson's ratio values for layers

An 11.8" diameter plate is loaded to 9000 lbs. on a pavement which is composed of 8" of A.C. with a mid-depth temperature of 68 degrees Fahrenheit, an E_{ac} = 754,200 psi and $u = 0.35$. The subgrade M_r = 10,000 psi and $u = 0.45$.

$$d_z = \frac{(1+u)s_0 a}{E}\left[\frac{1}{\sqrt{1+\left(\frac{z}{a}\right)^2}} + (1-2u)\left(\sqrt{1+\left(\frac{z}{a}\right)^2} - \frac{z}{a}\right)\right]$$

where:
d_z = deflection at depth z
u = Poisson's ratio
E = strength Modulus of the layer
s_0 = plate pressure
a = plate radius
z = depth deflection is measured at

$$s_0 = \frac{\textit{plate load}}{\textit{plate area}} = \frac{9000\ lbs.}{\left(\frac{pi*(11.8)^2}{4}\right)} = 82.30\ psi$$

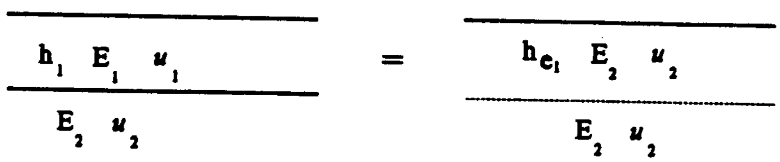
$$at\ z = 0" \qquad d_{z_0} = \frac{(1+0.35)(82.30)(5.9)}{754{,}200}\left[1+(1-2(0.35))(1)\right] = 0.0011299\ inches = 1.13\ mils$$

$$at\ z = 8" \qquad d_{z_8} = \frac{(1+0.35)(82.30)(5.9)}{754{,}200}\left[\frac{1}{\sqrt{1+\left(\frac{8}{5.9}\right)^2}} + (1-2(0.35))\left(\sqrt{1+\left(\frac{8}{5.9}\right)^2} - \frac{8}{5.9}\right)\right]$$

$$d_{z_8} = 0.000601\ inches = 0.601\ mils$$

$$Compression\ of\ A.C. = d_{z_0} - d_{z_8} = 1.13 - 0.601 = 0.5283\ mils$$

Equivalent Thickness



Where f = fudge factor for slippage between layers

$$h_e = f\,h_1\sqrt[3]{\frac{E_1}{E_2}*\frac{\left(1-u_2^{\,2}\right)}{\left(1-u_1^{\,2}\right)}} = (0.90)(8.0")\sqrt[3]{\frac{754,200}{10,000}*\frac{1-(0.45)^2}{1-(0.35)^2}} = 29.47"$$

$$d_{z_{29.47"}} = \frac{(1+0.45)(82.30)(5.9)}{10,000}\left[\frac{1}{\sqrt{1+\left(\frac{29.47}{5.9}\right)^2}}+\left(1-2(0.45)\right)\left(\sqrt{1+\left(\frac{29.47}{5.9}\right)^2}-\frac{29.47}{5.9}\right)\right]$$

$$d_{z_{29.47"}} = 0.01452\,inch = 14.52\,mils$$

$$d_{TOTAL} = d_{A.C.} + d_{subgrade} = 0.5283 + 14.52 = 15.05\,mils$$

AASHTO method:

$$d_0 = 1.5 s_0 a \left[\frac{1}{M_r \sqrt{1 + \left(\frac{D}{a} \sqrt[3]{\frac{E_p}{M_r}} \right)^2}} + \frac{\left[1 - \frac{1}{\sqrt{1 + \left(\frac{D}{a} \right)^2}} \right]}{E_p} \right]$$

$$d_0 = 1.5(82.30)(5.9) \left[\frac{1}{10{,}000 \sqrt{1 + \left(\frac{8}{5.9} \sqrt[3]{\frac{754{,}200}{10{,}000}} \right)^2}} + \frac{\left[1 - \frac{1}{\sqrt{1 + \left(\frac{8}{5.9} \right)^2}} \right]}{754{,}200} \right] = 0.012917\ \textit{inches} = 12.92\ \textit{mils}$$

NOTE: Since there is no base, $E_p = E_{ac}$, and since AC is at 68°F, there is no Temperature Adjustment Factor to d_0

Equivalent Thickness Transformation, same Poisson's ratio values for layers

asphalt layer transformed to subgrade material

$$h_e = 8 * \sqrt[3]{\frac{754,200}{10,000}} = 33.80"$$

$$d_{z_{33.80"}} = \frac{(1+0.35)(82.30)(5.9)}{10,000}\left[\frac{1}{\sqrt{1+\left(\frac{33.80}{5.9}\right)^2}} + (1-2(0.35))\left(\sqrt{1+\left(\frac{33.80}{5.9}\right)^2} - \frac{33.80}{5.9}\right)\right]$$

$$d_{z_{33.80"}} = 0.0129756\,\mathit{inches} = 12.9756\,\mathit{mils}$$

$$d_{TOTAL} = d_{A.C.} + d_{subgrade} = 0.5283\,(\mathit{found\ previously}) + 12.9756 = 13.50\,\mathit{mils}$$

Another Example of Equivalent Thickness using same Poisson's ratio for layers:

An 18" diameter plate is loaded to 18,000 lbs. on an A.C. pavement over a subgrade. The A.C. is 9" thick and has an E = 500,000 psi and $u = 0.34$. The subgrade M_r = 10,000 psi and $u = 0.45$. Calculate the center deflection.

Find the plate pressure:

$$s_0 = \frac{\textit{plate load}}{\textit{plate area}} = \frac{18{,}000}{\left(\frac{pi*(18)^2}{4}\right)} = 70.74\ psi$$

Find the deflection at the surface of the A.C.:

$$d_z = \frac{(1+u)s_0 a}{E}\left[\frac{1}{\sqrt{1+\left(\frac{z}{a}\right)^2}} + (1-2u)\left(\sqrt{1+\left(\frac{z}{a}\right)^2}\right) - \frac{z}{a}\right]$$

at surface, $z = 0$

$$d_{z=0} = \frac{(1+0.35)(70.74)(9)}{500{,}000}\left[1+(1-2(0.35))(1)\right] = 0.002235\ \textit{inches} = 2.235\ \textit{mils}$$

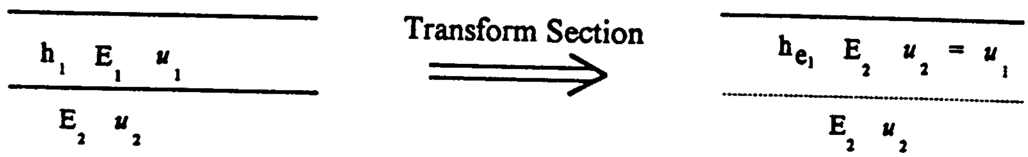
Find the deflection at the bottom of the A.C. layer at z = 9":

$$d_{z_{9''}} = \frac{(1+0.35)(70.74)(9)}{500,000}\left[\frac{1}{\sqrt{1+\left(\frac{9}{9}\right)^2}} + (1-2(0.35))\left(\sqrt{1+\left(\frac{9}{9}\right)^2} - \left(\frac{9}{9}\right)\right)\right]$$

$$d_{z_{9''}} = 0.001429\ \textit{inches} = 1.429\ \textit{mils}$$

$$A.C.\ Compression = d_{z_{0''}} - d_{z_{9''}} = 2.235 - 1.429 = 0.806\ \textit{mils}$$

Equivalent Thickness



$$h_e = f\, h_1 * \sqrt[3]{\frac{E_1}{E_2}}$$

where:

f = fudge factor for interface of layers to account for slippage
for the first structural interface, f = 0.90 for a two layer system
for a multi-layer system, f = 1.0 for the first interface, and f = 0.80 for all other

h_1 = original layer thickness

h_e = equivalent thickness

NOTE: Poisson's ratio is assumed to be the same for all layers (as Odemark assumed)

$$h_e = (0.90)(9)\sqrt[3]{\frac{500,000}{10,000}} = 29.84''\ \textit{equivalent thickness of asphalt}$$

Calculate the deflection at h_e:

$$d_{z_{29.84''}} = \frac{(1+0.35)(70.74)(9)}{10{,}000}\left[\frac{1}{\sqrt{1+\left(\frac{29.84}{9}\right)^2}}+(1-2(0.35))\left(\sqrt{1+\left(\frac{29.84}{9}\right)^2}-\frac{29.84}{9}\right)\right]$$

$$d_{z_{29.84''}} = 0.02862\ inches = 28.62\ mils$$

$$Total\ deflection = (d_{z_{0''}} - d_{z_{9''}}) + d_{z_{29.84''}} = 0.806 + 28.62 = 29.43\ mils = 0.2943\ inches$$

Appendix E depicts examples of the Modulus programs output and how the results need to be reviewed for accuracy and reasonableness.

APPENDIX E

DATE TESTED 8-26-93

JOB # 8-0-448 — TTI MODULUS ANALYSIS SYSTEM (SUMMARY REPORT) (Version 4.2)

District: 8
County: 84 POLK
Highway/Road: 32
LOG 9.47 - LOG 10.20
AMB. AIR 87°-91°
PVMNT SURFACE 126-131

	Thickness(in)	MODULI RANGE(psi) Minimum	Maximum	Poisson Ratio Values
Pavement: AC	6.00	50,000	3,000,001	H1: u = 0.35
Base: A.B.	5.00	4,000	150,000	H2: u = 0.35
Subbase: SUBGR.	36.00	4,000	80,000	H3: u = 0.40
Subgrade:	INFINITY	31,800		H4: u = 0.40

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (ksi): SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	Absolute ERR/Sens	Dpth to Bedrock
9.600	8,999	17.77	12.94	10.30	6.99	4.86	2.68	1.49	297.	7.4	26.5	26.1	0.38	71.64
9.700	8,999	27.90	19.30	11.96	6.21	3.68	1.82	0.95	109.	4.0	36.0	34.8	3.83	33.58 *
9.800	8,999	32.33	21.12	13.63	6.89	3.61	1.45	0.80	86.	4.6	21.6	46.4	3.51	31.67 *
9.900	8,999	20.54	15.68	12.58	8.88	6.44	3.47	1.21	268.	16.0	12.7	26.9	0.48	70.21
10.000	8,999	18.73	12.46	8.96	5.45	3.54	1.87	0.73	192.	7.2	39.4	33.1	0.60	50.89
10.100	8,999	32.12	19.62	12.66	6.58	3.55	1.35	0.77	81.	5.7	18.9	57.2	1.26	34.11 *
		0	8	12	18	24	36	60						
Mean:		24.90	16.85	11.68	6.83	4.28	2.11	0.99	172.	7.5	25.8	37.4	1.68	43.31
Std. Dev:		6.70	3.68	1.73	1.15	1.17	0.82	0.30	95.	4.4	10.3	12.2	1.58	13.89
Var Coeff(%):		26.90	21.86	14.80	16.79	27.43	38.73	30.32	55.	58.4	39.8	32.5	94.12	32.07

GOOD ERROR VALUES

DEPTH TO STIFF LAYER ≈ 3.61 ...

DUE TO THE PROXIMITY OF THE STIFF LAYER THE TWO VALUES OF SUBGR. SHOULD NOT BE AVG.. INSTEAD USE THE 1ST 36" OF SUBGR. AS REPRESENTATIVE VALUE

$M_R = 25,800$ psi

MEAN AC MIX ≈ 100°
E_{AC} @ 100° ≈ 161 ksi — GOOD

USING D=6 FOR A.C. DEPTH ONLY

TEMP. ADJ. FACTOR FOR A.C. @ 100°

172,000 psi ÷ 0.75 = 229,333 psi

DATE TESTED : 10-25-93

FILE # J:\RI9310\2P350 MIS.OUT

TTI MODULUS ANALYSIS SYSTEM (SUMMARY REPORT) (Version 4.2)

District: 2
County: 59 LIVINGSTON
Highway/Road: RTE36

MEAN AC MIX TEMP 79°

	Thickness(in)	MODULI RANGE(psi) Minimum	Maximum	Poisson Ratio Values
Pavement: AC.	3.00	150,000	3,000,001	H1: u = 0.35
Base: PCC	8.00	1,000,000	8,999,999	H2: u = 0.15
Subbase: AGGR. BASE	4.00	5,000	150,000	H3: u = 0.35
Subgrade:	285.00	15,000		H4: u = 0.40

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (ksi): SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	Absolute ERR/Sens	Dpth to Bedrock
7.100	9,023	6.40	4.93	4.05	3.75	3.44	2.81	1.71	240.	1297.9	150.0	24.0	5.43	300.00 *
7.200	9,071	4.47	4.12	3.97	3.71	3.44	2.85	1.83	1548.	4262.4	12.3	18.7	0.25	300.00
7.300	9,047	5.17	4.77	4.64	4.32	4.11	3.50	2.44	796.	6091.2	72.3	13.5	0.38	300.00
7.400	9,039	5.01	4.33	4.18	3.91	3.61	2.97	1.91	363.	5603.0	52.6	17.5	0.24	300.00
7.515	9,063	6.48	6.07	5.89	5.58	5.25	4.40	2.85	1025.	4080.3	26.4	10.7	0.46	300.00
7.600	9,135	5.38	4.81	4.56	4.32	3.99	3.30	2.07	464.	4886.5	47.8	15.9	0.40	300.00
7.700	9,063	6.16	5.30	5.22	4.81	4.49	3.62	2.28	317.	4327.2	39.1	14.5	0.83	300.00
7.800	9,047	4.60	4.12	3.93	3.67	3.44	2.81	1.83	568.	5678.1	18.9	18.9	0.50	300.00
7.900	8,999	4.60	3.96	3.72	3.55	3.31	2.73	1.79	337.	6930.0	55.5	18.6	0.73	300.00
8.000	9,127	5.66	5.10	4.93	4.65	4.36	3.66	2.48	489.	5731.4	32.7	13.5	0.22	300.00
8.100	8,943	11.66	10.15	7.69	6.07	5.33	4.11	2.60	150.	1000.0	7.3	15.0	10.53	300.00 *
		0	8	12	18	24	36	60						
Mean:		5.96	5.24	4.80	4.39	4.07	3.34	2.16	573.	4535.3	46.8	16.4	1.81	300.00
Std. Dev:		2.02	1.74	1.16	0.83	0.72	0.57	0.39	410.	1883.1	39.5	3.6	3.26	0.00
Var Coeff(%):		33.90	33.21	24.10	18.79	17.77	17.02	17.86	72.	41.5	84.4	22.0	179.62	0.00

GOOD GOOD GOOD

Job # 9-P-307 FILE J:\RI9310\FWD\RI9310A\9P307XXC.FWD

DATE TESTED 8-23-93 TTI MODULUS ANALYSIS SYSTEM (SUMMARY REPORT) (Version 4.2)

District: 9 0
County: TEXAS 4 HOWEL
Highway/Road: EBDL RTE 60-63
PRE-OVERLAY RESULTS

		Thickness(in)	MODULI RANGE(psi) Minimum	Maximum	Poisson Ratio Values
Pavement:	PCCP	8.00	500,000	8,999,999	H1: u = 0.15
Base:	AGGR. BASE	4.00	5,000	150,000	H2: u = 0.35
Subbase:		0.00	0	0	H3: u = 0.40
Subgrade:		171.80	15,000		H4: u = 0.40

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (ksi): SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	Absolute ERR/Sens	Dpth to Bedrock
10.408	8,999	3.70	3.52	3.38	3.09	2.84	2.33	1.49	8245.	24.6	0.0	19.4	0.40	300.00
10.507	8,999	5.48	5.19	5.29	4.47	4.07	3.23	1.79	4399.	15.0	0.0	15.1	1.95	***
10.645	8,999	3.93	3.67	3.57	3.18	2.88	2.28	1.29	6186.	21.7	0.0	21.6	0.61	160.37
10.712	8,999	4.96	4.80	4.57	4.33	4.06	3.39	1.92	8306.	21.2	0.0	11.5	0.48	169.59
10.808	8,999	4.41	4.25	3.96	3.90	3.62	3.03	1.86	9000.	33.2	0.0	13.1	1.27	300.00 *
10.913	8,999	3.06	2.93	2.68	2.44	2.21	1.67	0.93	6781.	28.4	0.0	30.7	1.11	146.80
11.006	8,999	4.01	3.86	3.59	3.16	2.85	2.16	1.08	4837.	21.1	0.0	24.3	1.21	114.09
11.111	8,999	4.91	4.67	4.75	3.94	3.50	2.67	1.39	3934.	17.4	0.0	19.4	2.31	***
11.215	8,999	3.50	3.31	3.21	2.83	2.48	1.90	1.02	5675.	24.6	0.0	27.3	1.28	131.92
11.309	8,999	6.57	6.22	6.34	5.46	4.97	3.98	2.29	3827.	51.8	0.0	11.5	1.78	***
11.414	8,999	5.21	5.04	4.83	4.50	4.11	3.36	2.01	5990.	98.4	0.0	12.5	0.63	229.18
11.509	8,999	4.70	4.50	4.35	3.87	3.51	2.75	1.49	5158.	17.6	0.0	17.7	0.97	148.29
11.615	8,999	4.37	4.17	3.97	3.66	3.33	2.65	1.60	6257.	23.1	0.0	17.5	0.46	300.00
11.706	8,999	4.43	4.21	4.02	3.45	3.06	2.29	1.19	3976.	16.6	0.0	23.8	1.38	129.71
11.916	8,999	5.45	5.29	5.09	4.69	4.32	3.63	2.34	6350.	53.4	0.0	11.4	0.69	300.00
12.009	8,999	5.29	5.10	4.89	4.48	4.11	3.38	2.03	5673.	94.6	0.0	12.7	0.57	300.00
12.115	8,999	4.83	4.37	4.67	3.59	3.16	2.34	1.09	3144.	17.5	0.0	23.9	3.35	***
12.208	8,999	4.50	4.24	4.04	3.70	3.33	2.75	1.60	6125.	23.4	0.0	17.2	0.61	177.12
12.313	8,999	3.67	3.58	3.19	3.19	2.99	2.45	1.47	9000.	87.7	0.0	17.4	2.41	300.00 *
12.407	8,999	4.42	4.20	3.99	3.65	3.29	2.63	1.52	6035.	6.0	0.0	19.8	0.31	162.01 *
12.511	8,999	8.68	7.69	6.74	6.11	5.33	3.90	1.80	1229.	138.9	0.0	13.9	1.47	113.35 *
12.616	8,999	6.01	5.60	5.95	4.83	4.30	3.35	1.84	3446.	14.1	0.0	15.3	2.94	***
12.709	8,999	3.95	3.77	3.65	3.31	2.99	2.45	1.38	7144.	27.2	0.0	18.9	0.70	151.77
12.813	8,999	5.76	5.59	5.23	5.18	4.95	2.16	1.49	2044.	7.1	0.0	23.7	11.80	47.28 *
12.907	8,999	5.01	4.78	4.60	4.24	3.89	3.20	1.99	6349.	22.0	0.0	13.7	0.26	300.00
13.011	8,999	3.70	3.53	3.30	3.06	2.77	2.15	1.16	6692.	22.4	0.0	22.5	0.87	137.96
13.116	8,999	4.25	4.02	3.77	3.60	3.32	2.65	1.36	7491.	20.5	0.0	16.5	1.01	122.16
13.209	8,999	8.49	8.04	8.22	7.06	6.40	5.09	2.75	2880.	38.1	0.0	9.1	1.89	***
13.314	8,999	8.14	4.85	5.91	3.73	3.20	2.28	1.12	779.	118.1	0.0	26.0	10.84	*** *
13.407	8,999	6.21	6.04	5.87	5.51	5.16	4.42	2.96	7503.	29.6	0.0	8.2	0.35	300.00
13.512	8,999	4.07	3.97	3.76	3.46	3.15	2.51	1.44	7149.	5.9	0.0	19.7	0.87	174.76
13.617	8,999	5.30	4.98	5.15	4.36	3.93	3.20	1.82	4792.	23.2	0.0	14.9	2.19	***
13.713	8,999	4.98	4.83	4.64	4.28	3.97	3.27	2.05	6881.	21.3	0.0	12.9	0.55	300.00
13.806	8,999	5.11	4.82	4.81	4.20	3.84	3.10	1.88	5433.	5.0	0.0	16.5	1.27	300.00 *
13.912	8,999	3.55	3.46	3.18	2.97	2.72	2.22	1.34	8428.	10.6	0.0	21.6	0.95	300.00
14.009	8,999	4.97	4.77	4.76	4.18	4.04	3.25	2.02	6984.	21.9	0.0	12.8	1.73	300.00
14.117	8,999	5.16	4.38	5.85	3.28	2.77	1.89	0.71	1816.	10.2	0.0	34.1	8.21	*** *
14.212	8,999	6.40	6.64	5.83	6.57	6.50	6.48	1.93	7036.	50.9	0.0	7.0	10.19	*** *
14.308	8,999	3.24	2.90	2.82	2.41	2.14	1.57	0.76	5047.	27.7	0.0	35.2	1.07	101.12
14.416	8,999	3.28	3.11	2.87	2.67	2.40	1.86	0.92	7086.	27.0	0.0	26.7	0.83	105.13
14.512	8,999	7.14	7.54	6.06	6.04	5.35	4.13	2.24	3174.	12.0	0.0	12.0	3.81	***
14.617	8,999	4.53	4.67	3.88	3.95	3.46	2.60	1.34	5131.	18.3	0.0	18.5	4.23	***
14.710	8,999	4.78	4.50	4.52	3.86	3.46	2.73	1.46	4653.	17.7	0.0	18.5	1.65	***
14.814	8,999	6.34	5.61	5.01	4.62	4.08	3.05	1.45	2642.	17.2	0.0	18.3	1.63	112.35
14.908	8,999	4.17	4.06	3.90	3.51	3.19	2.46	1.38	6129.	6.3	0.0	21.0	1.45	167.35 *
15.013	8,999	4.64	4.53	4.38	3.94	3.67	2.97	1.80	6662.	22.9	0.0	14.8	1.16	300.00
15.117	8,999	4.19	3.96	3.84	3.40	3.07	2.39	1.26	5445.	21.0	0.0	20.8	0.80	131.08
15.210	8,999	3.85	3.59	3.62	2.98	2.60	1.93	0.92	4273.	17.3	0.0	28.8	2.17	***
15.315	8,999	3.63	3.46	3.43	2.97	2.71	2.18	1.25	7246.	7.2	0.0	24.0	1.39	160.80 *
0.012	8.999	4.31	3.91	4.30	3.22	2.80	2.12	1.[illegible]	3547.	17.9	0.0	24.7	1.09	***

[illegible]													[illegible]	[illegible]
0.209	8.999	3.31	3.13	2.98	2.62	2.39	1.85	1.11	6519.	26.9	0.0	27.6	0.85	136.65
0.313	8.999	5.80	5.43	5.43	4.61	4.09	3.11	1.67	3323.	14.9	0.0	16.8	1.71	154.37
0.407	8.999	4.66	4.43	4.32	3.87	3.41	2.68	1.36	4949.	16.4	0.0	18.4	1.28	119.71
0.511	8.999	3.30	3.17	2.89	2.60	2.37	1.79	0.89	6085.	28.6	0.0	28.9	1.24	108.19
0.616	8.999	3.47	3.29	3.14	2.73	2.45	1.87	0.98	5611.	24.4	0.0	28.2	1.07	123.06
0.709	8.999	6.25	6.03	5.92	5.44	5.08	4.24	2.67	6136.	26.9	0.0	9.4	0.61	300.00
0.813	8.999	5.72	5.55	5.34	4.92	4.53	3.76	2.33	5679.	91.4	0.0	11.1	0.56	300.00
0.906	8.999	5.36	5.07	5.11	4.30	3.85	3.02	1.74	3941.	16.4	0.0	16.9	1.90	***
1.011	8.999	5.21	4.96	4.67	4.33	3.94	3.15	1.76	5249.	5.0	0.0	16.2	0.88	168.30 *
1.116	8.999	4.59	4.49	4.25	4.10	3.87	3.46	2.10	9000.	21.6	0.0	11.9	2.21	300.00 *
1.209	8.999	5.04	4.93	4.75	4.38	4.02	3.27	2.07	6155.	100.2	0.0	12.8	1.00	300.00
1.314	8.999	4.50	4.26	4.07	3.72	3.34	2.70	1.43	5860.	23.7	0.0	17.6	0.40	130.59
1.407	8.999	4.36	4.24	3.95	3.69	3.40	2.71	1.52	6707.	22.7	0.0	16.6	0.93	164.70
1.512	8.999	4.43	4.27	4.12	3.76	3.43	2.79	1.59	6794.	21.3	0.0	16.0	0.65	300.00
1.617	8.999	5.73	6.10	4.92	5.18	4.59	3.48	1.91	4678.	22.1	0.0	12.9	5.23	***
1.710	8.999	4.94	4.79	4.60	4.28	3.97	3.26	2.03	7134.	22.4	0.0	12.7	0.54	300.00
1.814	8.999	5.88	5.67	5.46	5.20	4.78	4.09	2.68	7334.	27.4	0.0	9.3	0.35	300.00
1.907	8.999	5.01	4.82	4.76	4.30	3.90	3.10	1.66	5886.	5.0	0.0	15.7	1.27	144.90 *
2.012	8.999	4.14	4.08	3.74	3.69	3.44	2.88	1.86	9000.	31.0	0.0	14.3	2.00	300.00 *
2.117	8.999	4.09	3.95	3.73	3.47	3.14	2.62	1.57	7654.	26.9	0.0	16.9	0.67	193.47
2.210	8.999	4.64	4.49	4.42	3.84	3.52	2.73	1.49	5395.	5.7	0.0	19.2	1.67	153.99 *
2.314	8.999	5.68	5.55	5.30	5.00	4.67	3.90	2.45	7141.	29.3	0.0	9.9	0.56	300.00
2.409	8.999	5.49	5.24	5.16	4.60	4.22	3.33	2.00	4920.	22.5	0.0	13.8	1.15	300.00
2.510	8.999	5.08	4.83	4.60	4.22	3.90	3.18	1.98	5960.	22.3	0.0	14.1	0.32	300.00
2.615	8,999	5.40	5.23	4.97	4.51	4.11	3.22	1.74	4708.	21.5	0.0	14.6	0.98	155.47
2.708	8.999	5.09	4.80	4.52	4.15	3.75	3.00	1.80	4832.	47.8	0.0	15.8	0.28	232.21
2.813	8,999	4.86	4.66	4.42	4.01	3.64	2.94	1.75	5441.	23.8	0.0	16.1	0.66	214.40
		6	8	72	78	24	36	60						
Means:		4.91	4.66	4.50	4.04	3.68	2.92	1.65	5656.	29.1	0.0	17.8	1.78	183.81
Std. Dev:		1.12	1.03	1.00	0.93	0.88	0.80	0.48	1789.	26.2	0.0	6.1	2.22	92.75
Var Coeff(%):		22.87	22.08	22.24	22.96	23.89	27.47	29.06	32.	89.9	0.0	34.2	124.86	50.46

GOOD GOOD GOOD

DATE TESTED: 9-7-93

FILE # IPS36X2C.FWD — TTI MODULUS ANALYSIS SYSTEM (SUMMARY REPORT) (Version 4.2)

District: 1			MODULI RANGE(psi)			
County: 3 ATCHISON		Thickness(in)	Minimum	Maximum	Poisson Ratio Values	
Highway/Road: 136	Pavement: AC	7.50	50,000	3,000,001	H1: u = 0.35	
AMB. AIR 55°-65°	Base: SOIL CEM.	6.00	5,000	3,000,001	H2: u = 0.20	
PVMT SURF. 45-75°	Subbase: SUBGR.	36.00	4,000	80,000	H3: u = 0.40	
LOG 0.00 - LOG 6.90	Subgrade:	137.50	15,000		H4: u = 0.40	

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (ksi): SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	Absolute ERR/Sens	Dpth to Bedrock
0.339	8,999	7.42	7.13	6.88	6.76	6.53	5.61	3.92	1686.	1888.8	4.0	6.3	1.83	300.00 *
0.439	8,999	6.21	5.20	4.87	4.57	4.26	3.66	2.52	513.	1698.8	56.7	5.7	0.25	300.00 *
0.539	8,999	6.38	5.48	5.27	5.09	4.86	4.27	3.09	3000.	9.0	11.3	24.3	10.45	300.00 *
0.639	8,999	6.40	5.55	5.22	5.01	4.80	4.23	3.16	3000.	9.0	11.3	24.4	10.24	300.00 *
0.739	8,999	8.02	7.44	7.15	7.00	6.81	6.29	5.22	1761.	1130.1	5.9	5.9	3.53	300.00 *
0.839	8,999	4.72	4.43	4.12	3.94	3.76	3.29	2.40	1942.	2631.2	17.7	8.8	1.13	300.00 *
0.939	8,999	7.12	6.22	6.01	5.79	5.47	4.62	3.23	3000.	259.4	8.7	11.1	3.76	300.00 *
1.039	8,999	14.35	10.91	9.37	7.74	6.36	4.44	2.33	213.	73.7	17.5	9.8	0.16	171.10
1.139	8,999	12.84	10.77	9.52	8.03	6.80	4.67	2.65	389.	103.0	10.5	12.6	0.40	272.68
1.239	8,999	9.79	8.61	7.83	6.89	6.10	4.72	2.93	680.	167.0	18.4	7.8	0.39	300.00
1.339	8,999	19.75	14.38	12.03	9.81	8.07	5.55	2.85	122.	61.2	13.6	8.0	0.35	168.42
1.439	8,999	12.58	11.58	10.79	9.64	8.40	5.83	2.88	1268.	45.1	4.0	21.8	0.93	158.55 *
1.539	8,999	17.64	14.47	12.47	10.12	8.27	5.31	2.67	290.	31.3	10.3	10.4	0.50	164.53
1.639	8,999	15.92	13.47	11.37	9.49	8.01	5.67	2.95	402.	8.0	39.7	4.7	1.07	176.70
1.739	8,999	17.61	14.10	12.42	10.69	8.99	6.12	3.15	176.	184.7	5.2	14.9	0.32	184.18
1.839	8,999	14.45	12.00	10.58	8.96	7.56	5.46	2.91	293.	106.8	11.2	9.1	0.61	189.57
1.939	8,999	15.77	12.75	11.21	9.36	7.79	5.34	2.89	252.	86.3	10.3	10.1	0.13	214.86
2.039	8,999	12.61	10.56	9.43	8.02	6.70	4.68	2.41	404.	109.8	10.5	12.5	0.24	164.65
2.139	8,999	9.64	8.90	8.29	7.43	6.53	4.82	2.54	1864.	56.2	5.7	18.8	0.16	175.78
2.239	8,999	14.96	12.92	11.50	9.16	7.01	4.59	2.60	501.	26.4	6.7	29.2	2.21	257.55
2.339	8,999	9.15	8.31	7.68	6.87	6.11	4.63	2.63	1830.	5.0	55.6	6.8	0.49	237.72
2.439	8,999	14.41	12.70	11.43	9.91	8.51	6.06	3.01	445.	148.9	4.7	15.8	0.57	155.05
2.539	8,999	13.26	12.12	10.78	9.11	7.68	5.45	2.81	810.	6.3	21.4	7.9	0.91	169.26
2.639	8,999	29.99	25.75	21.14	16.41	12.52	6.71	3.18	206.	5.2	5.1	17.4	1.19	76.07 *
2.739	8,999	8.83	8.24	7.63	6.83	6.06	4.80	2.84	1639.	95.2	14.5	8.3	0.59	277.13
2.839	8,999	8.25	7.56	7.07	6.48	5.87	4.74	2.85	1981.	86.1	21.3	6.6	0.45	300.00 *
2.939	8,999	14.44	12.14	10.88	9.49	8.13	5.76	2.89	470.	46.2	14.4	6.9	1.04	159.57
3.039	8,999	10.48	9.81	8.90	7.55	6.34	4.51	2.52	1170.	36.3	7.9	18.8	1.49	229.26
3.139	8,999	13.75	12.75	11.18	9.47	8.06	5.72	2.69	763.	26.0	8.6	11.0	1.50	129.26
3.239	8,999	11.03	10.18	9.46	8.48	7.53	5.82	2.58	1453.	41.2	11.8	7.2	0.21	107.73
3.339	8,999	11.80	10.83	9.97	8.82	7.71	5.76	2.92	1020.	86.6	8.7	9.5	0.33	156.78
3.439	8,999	10.51	9.70	8.85	7.64	6.54	4.66	2.53	1176.	57.9	7.1	18.1	0.76	203.44
3.539	8,999	20.04	14.77	12.56	9.98	7.93	5.08	2.40	141.	46.8	11.1	10.5	0.19	131.91
3.639	8,999	11.55	10.81	10.04	8.77	7.49	5.24	2.32	1484.	17.7	4.1	39.5	0.79	113.47
3.739	8,999	41.00	34.95	28.31	19.74	13.02	6.49	2.57	96.	6.7	4.0	22.3	4.63	51.87 *
3.839	8,999	12.13	10.65	9.34	7.75	6.45	4.52	2.36	701.	6.1	51.8	7.0	0.61	169.06
3.939	8,999	11.97	9.60	8.31	7.13	6.19	4.54	2.41	294.	110.8	22.0	7.9	0.68	175.32
4.039	8,999	18.06	15.64	13.95	11.80	9.86	6.68	2.86	360.	74.2	4.4	15.8	0.58	111.30
4.139	8,999	11.04	9.74	8.79	7.73	6.71	5.02	2.74	780.	64.4	17.2	7.5	0.32	200.67
4.239	8,999	12.49	11.53	10.56	9.31	8.09	5.68	2.66	1198.	44.6	4.4	21.4	0.55	132.07
4.339	8,999	10.67	9.41	8.52	7.53	6.53	4.80	2.59	883.	61.8	15.7	8.6	0.48	193.28
4.439	8,999	15.57	14.05	12.78	10.58	8.02	4.90	2.19	607.	14.8	4.9	49.2	2.38	118.28 *
4.539	8,999	16.64	13.59	11.78	9.62	7.86	5.18	2.76	298.	37.1	11.1	10.2	0.25	202.48
5.439	8,999	22.39	20.02	15.18	10.11	7.08	4.41	2.35	184.	5.0	17.5	14.2	6.95	86.71 *
5.539	8,999	8.04	7.21	6.66	5.95	5.31	4.15	2.45	1575.	23.8	44.0	5.9	0.41	263.11
5.639	8,999	8.72	8.01	7.44	6.71	6.01	4.67	2.66	1382.	215.1	9.6	10.8	0.26	230.35
5.739	8,999	13.59	11.40	10.13	8.64	7.31	5.18	2.89	366.	106.4	10.6	10.3	0.31	243.70
5.839	8,999	15.20	12.72	11.12	9.28	7.91	5.85	3.31	390.	17.1	28.0	4.6	0.40	253.13
5.939	8,999	12.97	11.75	10.65	9.36	8.19	5.87	2.69	995.	27.6	9.0	9.3	0.56	123.78
6.039	8,999	26.57	21.05	17.69	14.13	11.19	7.39	3.60	173.	10.6	11.6	5.7	0.34	147.64

6.239	8.999	8.45	7.44	6.85	6.19	5.51	4.25	2.56	625.	523.9	5.8	20.0	0.41	300.11
6.339	8.999	33.11	24.91	19.67	14.69	11.40	7.21	3.15	105.	5.9	15.5	5.1	0.96	105.84
6.439	8.999	11.85	10.65	9.86	8.83	7.62	5.78	3.20	1036.	85.1	5.8	6.6	0.55	239.19
6.539	8.999	9.01	7.96	7.24	6.46	5.76	4.54	2.79	718.	215.5	21.8	7.3	0.37	300.00
6.639	8.999	7.45	6.94	6.59	6.13	5.61	4.52	2.71	3000.	246.2	4.0	23.4	0.85	287.23 *
6.739	8.999	12.35	11.00	9.88	8.49	7.26	5.32	2.73	707.	52.6	12.5	8.8	0.57	161.58
6.839	8.999	14.18	12.34	11.07	9.61	8.23	5.86	2.85	649.	17.3	16.4	6.5	0.61	143.57
		0	8	12	18	24	36	60						
Mean:		13.57	11.65	10.28	8.69	7.33	5.23	2.83	937	201.3	14.4	12.7	1.27	187.88
Std. Dev:		6.57	5.22	4.02	2.70	1.77	0.84	0.46	732.	481.0	12.4	8.5	2.10	89.12
Var Coeff(%):		48.45	44.78	39.13	31.09	24.12	15.97	16.33	83.	100.0	86.1	66.8	166.02	47.57

MEAN AC MIX TEMP ≈ 68°
∴ E_{AC} 65° ≈ 847,000 psi

GOOD E_{AC}

GOOD VALUE FOR SOIL CEM.

GOOD AVG MR = 13.6 ksi

GOOD ERROR VALUE.

15.59'
DEPTH TO STIFF LAYER IS GREATER THAN 10', THEREFORE AN AVG MR CAN BE USED

J:\ RI9310\ FWD\ PRE-RITAB\ IP536X2C.FWD

DATE TESTED: 5-3-94 TTI MODULUS ANALYSIS SYSTEM (SUMMARY REPORT) (Version 4.2)

District: 1
County: 3
Highway/Road: 136

	Thickness(in)	MODULI RANGE(psi) Minimum	Maximum	Poisson Ratio Values
Pavement: AC	7.50	50,000	3,000,001	H1: u = 0.35
Base: SOIL CEM.	6.00	5,000	3,000,001	H2: u = 0.20
Subbase:	0.00	0	0	H3: u = 0.35
Subgrade:	173.50	15,000		H4: u = 0.40

AVG AC TEMP ≈ 71°

Station	Load (lbs)	R1	R2	R3	R4	R5	R6	R7	SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	ERR/Sens	Absolute Dpth to Bedrock
0.339	8,999	7.42	7.13	6.88	6.76	6.53	5.61	3.92	1951.	1008.9	0.0	6.5	3.24	300.00 *
0.439	8,999	6.21	5.20	4.87	4.57	4.26	3.66	2.52	604.	3000.0	0.0	12.2	1.67	300.00 *
0.539	8,999	6.38	5.48	5.27	5.09	4.86	4.27	3.09	1013.	2688.9	0.0	9.0	2.53	300.00 *
0.639	8,999	6.40	5.55	5.22	5.01	4.80	4.23	3.16	960.	2751.4	0.0	9.2	2.44	300.00 *
0.739	8,999	8.02	7.44	7.15	7.00	6.81	6.29	5.22	1659.	1415.5	0.0	5.5	2.91	300.00 *
0.839	8,999	4.72	4.43	4.12	3.94	3.76	3.29	2.40	1923.	3000.0	0.0	10.4	1.18	300.00 *
0.939	8,999	7.12	6.22	6.01	5.79	5.47	4.62	3.23	834.	2451.9	0.0	8.2	1.44	300.00 *
1.039	8,999	14.35	10.91	9.37	7.74	6.36	4.44	2.33	179.	137.8	0.0	12.6	0.86	171.10
1.139	8,999	12.84	10.77	9.52	8.03	6.80	4.67	2.65	418.	83.9	0.0	11.6	0.37	272.68
1.239	8,999	9.79	8.61	7.83	6.89	6.10	4.72	2.93	583.	310.3	0.0	10.8	0.83	300.00
1.339	8,999	19.75	14.38	12.03	9.81	8.07	5.55	2.85	106.	102.8	0.0	10.1	1.20	168.42
1.439	8,999	12.58	11.58	10.79	9.64	8.40	5.83	2.88	1174.	19.0	0.0	8.9	1.51	158.55
1.539	8,999	17.64	14.47	12.47	10.12	8.27	5.31	2.67	289.	31.4	0.0	10.3	0.51	164.53
1.639	8,999	15.92	13.47	11.37	9.49	8.01	5.67	2.95	274.	78.8	0.0	9.8	1.74	176.70
1.739	8,999	17.61	14.10	12.42	10.69	8.99	6.12	3.15	203.	105.6	0.0	8.8	0.70	184.18
1.839	8,999	14.45	12.00	10.58	8.96	7.56	5.46	2.91	293.	117.1	0.0	10.0	0.82	189.57
1.939	8,999	15.77	12.75	11.21	9.36	7.79	5.34	2.89	252.	86.9	0.0	10.2	0.14	214.86
2.039	8,999	12.61	10.56	9.43	8.02	6.70	4.68	2.41	416.	96.9	0.0	11.5	0.19	164.65
2.139	8,999	9.64	8.90	8.29	7.43	6.53	4.82	2.54	1404.	90.3	0.0	10.3	0.83	175.78
2.239	8,999	14.96	12.92	11.50	9.16	7.01	4.59	2.60	532.	6.2	0.0	14.7	1.69	257.55
2.339	8,999	9.15	8.31	7.68	6.87	6.11	4.63	2.63	1101.	191.2	0.0	10.7	0.35	237.72
2.439	8,999	14.41	12.70	11.43	9.91	8.51	6.06	3.01	850.	12.3	0.0	9.6	0.94	155.05
2.539	8,999	13.26	12.12	10.78	9.11	7.68	5.45	2.81	878.	9.3	0.0	11.2	1.25	169.26
2.639	8,999	29.99	25.75	21.14	16.41	12.52	6.71	3.18	175.	5.0	0.0	8.4	2.85	76.07 *
2.739	8,999	8.83	8.24	7.63	6.83	6.06	4.80	2.84	1519.	163.6	0.0	10.2	0.75	277.13
2.839	8,999	8.25	7.56	7.07	6.48	5.87	4.74	2.85	1149.	449.5	0.0	9.5	0.27	300.00
2.939	8,999	14.44	12.14	10.88	9.49	8.13	5.76	2.89	330.	132.8	0.0	9.2	0.51	159.57
3.039	8,999	10.48	9.81	8.90	7.55	6.34	4.51	2.52	1183.	12.3	0.0	12.9	1.32	229.26
3.139	8,999	13.75	12.75	11.18	9.47	8.06	5.72	2.69	844.	9.9	0.0	10.5	1.55	129.26
3.239	8,999	11.03	10.18	9.46	8.48	7.53	5.82	2.58	1071.	146.5	0.0	8.4	0.31	107.73
3.339	8,999	11.80	10.83	9.97	8.82	7.71	5.76	2.92	986.	86.4	0.0	8.8	0.40	156.78
3.439	8,999	10.51	9.70	8.85	7.64	6.54	4.66	2.53	1210.	21.9	0.0	11.8	0.72	203.44
3.539	8,999	20.04	14.77	12.56	9.98	7.93	5.08	2.40	138.	49.7	0.0	10.8	0.13	131.91
3.639	8,999	11.55	10.81	10.04	8.77	7.49	5.24	2.32	1163.	21.1	0.0	10.1	1.71	113.47
3.739	8,999	41.00	34.95	26.31	19.74	13.02	6.49	2.57	81.	5.0	0.0	7.4	8.25	51.87 *
3.839	8,999	12.13	10.65	9.34	7.75	6.45	4.52	2.36	633.	36.3	0.0	12.5	1.21	169.06
3.939	8,999	11.97	9.60	8.31	7.13	6.19	4.54	2.41	236.	277.5	0.0	12.2	1.26	175.32
4.039	8,999	18.06	15.64	13.95	11.80	9.86	6.68	2.86	419.	29.1	0.0	8.2	0.40	111.30
4.139	8,999	11.04	9.74	8.79	7.73	6.71	5.02	2.74	619.	165.8	0.0	10.4	0.57	200.67
4.239	8,999	12.49	11.53	10.56	9.31	8.09	5.68	2.66	1040.	28.6	0.0	9.2	1.15	132.07
4.339	8,999	10.67	9.41	8.52	7.53	6.53	4.80	2.59	1121.	46.9	0.0	11.3	0.94	193.28
4.439	8,999	15.57	14.05	12.78	10.58	8.02	4.90	2.19	553.	5.0	0.0	13.3	3.25	118.28 *
4.539	8,999	16.64	13.59	11.78	9.62	7.86	5.18	2.76	298.	39.3	0.0	10.6	0.35	202.48
5.439	8,999	22.39	20.02	15.18	10.11	7.08	4.41	2.35	187.	5.0	0.0	15.6	7.21	86.71 *
5.539	8,999	8.04	7.21	6.66	5.95	5.31	4.15	2.45	1032.	322.2	0.0	11.9	0.51	263.11
5.639	8,999	8.72	8.01	7.44	6.71	6.01	4.67	2.66	1191.	259.5	0.0	10.2	0.32	230.35
5.739	8,999	13.59	11.40	10.13	8.64	7.31	5.18	2.89	373.	104.3	0.0	10.5	0.35	243.70
5.839	8,999	15.20	12.72	11.12	9.28	7.91	5.85	3.31	265.	120.5	0.0	9.5	1.59	253.13
5.939	8,999	12.57	11.75	10.65	[illegible]	[illegible]	5.27	2.49	[illegible]	97.5	0.0	9.1	0.59	177.79

6.139	8.999	11.80	10.77	10.07	9.10	8.19	6.34	3.47	892.	199.2	0.0	7.5	0.28	215.22
6.239	8.999	8.48	7.44	6.85	6.19	5.51	4.25	2.58	692.	435.4	0.0	11.6	0.24	300.00
6.339	8.999	33.11	24.91	19.67	14.69	11.40	7.21	3.15	86.	16.1	0.0	7.8	1.96	109.84
6.439	8.999	11.85	10.65	9.86	8.93	7.82	5.78	3.20	1041.	85.1	0.0	8.7	0.56	239.19
6.539	8.999	9.01	7.96	7.24	6.46	5.76	4.54	2.79	582.	461.1	0.0	11.0	0.89	300.00
6.639	8.999	7.45	6.94	6.59	6.13	5.61	4.52	2.71	1836.	444.6	0.0	9.4	0.44	287.23
6.739	8.999	12.35	11.00	9.88	8.49	7.28	5.32	2.73	1012.	14.4	0.0	11.0	1.41	161.58
6.839	8.999	14.18	12.34	11.07	9.61	8.23	5.86	2.85	515.	77.6	0.0	9.1	0.29	143.87
		0	8	12	18	24	36	60						
Mean:		13.57	11.65	10.23	8.69	7.33	5.23	2.83	750	381.5	0.0	10.1	1.29	157.08
Std. Dev:		6.57	5.22	4.02	2.70	1.77	0.84	0.46	491.	782.1	0.0	1.9	1.46	89.18
Var Coeff(%):		48.45	44.78	39.13	31.09	24.12	15.97	16.33	65.	100.0	0.0	18.3	113.17	47.67

GOOD

E_{AC} @ 70° ≈ 696 KSI

✓ OK E_{AC}

M_r = 10,100 psi

$M_{r\,DES.} = (0.33)\,10{,}100$

= 3333 psi

GOOD
SOIL CEMENT
VALUES

TAF @ 71° ≈ 0.98

$\boxed{750{,}000 \div 0.98 = 765{,}306 \text{ psi}}$

ATE TESTED 8-30-93

FILE # 7P360XXC.OUT   TTI MODULUS ANALYSIS SYSTEM (SUMMARY REPORT)   (Version 4.2)

District: 7 0
County: NEWTON / BARRY
Highway/Road: RTE 60
LOG 24.36 - LOG 27.36
LOG 0.00 - LOG 3.00

	Thickness(in)	MODULI RANGE(psi) Minimum	Maximum	Poisson Ratio Values
Pavement: A.C.	3.00	50,000	2,500,000	H1: u = 0.35
Base: AGGR. BASE	4.00	5,000	200,000	H2: u = 0.35
Subbase: SUBGR.	36.00	5,000	70,000	H3: u = 0.40
Subgrade: SUBGR.	13.80	8,000		H4: u = 0.40

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (ksi): SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	Absolute ERR/Sens	Dpth to Bedrock
2.900	8,999	18.07	11.44	8.58	4.73	2.91	1.26	0.51	594.	32.1	22.2	8.2	1.95	53.81
2.800	8,999	18.38	12.29	8.91	4.82	2.74	1.20	0.66	371.	14.7	24.0	8.7	2.36	50.11
2.700	8,999	23.84	15.85	11.47	6.02	3.36	1.49	0.87	761.	5.0	30.3	4.4	1.52	48.01 *
2.600	8,999	28.25	20.25	15.21	9.04	5.79	2.66	0.76	758.	7.0	16.0	2.8	0.73	68.44
2.500	8,999	38.56	28.28	22.09	12.41	7.44	2.75	0.76	652.	5.0	9.5	4.2	2.23	54.27 *
2.400	8,999	35.51	26.33	20.24	12.64	8.28	4.17	1.33	712.	5.0	12.6	1.7	0.69	76.86 *
2.290	8,999	30.36	21.16	15.97	8.71	5.05	1.95	0.54	689.	5.8	14.8	4.9	1.92	51.35
2.200	8,999	17.32	9.81	5.98	2.07	0.79	0.55	0.38	605.	7.1	69.6	20.2	9.21	122.49
2.100	8,999	29.35	19.95	14.26	7.15	3.90	1.29	0.48	641.	5.0	18.0	7.6	1.49	45.99 *
2.000	8,999	24.97	13.40	8.88	3.69	1.90	0.97	0.57	388.	6.6	37.5	7.4	2.81	57.25
1.900	8,999	22.60	14.22	10.11	4.65	2.39	1.14	0.61	679.	5.0	40.0	5.8	3.17	47.81 *
1.800	8,999	32.52	23.26	17.02	10.05	5.94	1.92	0.39	398.	32.1	8.1	13.0	1.70	52.96
1.700	8,999	24.80	17.90	11.69	5.04	1.72	0.13	0.36	495.	6.3	22.2	21.1	57.95	52.54 *
1.600	8,999	33.41	24.73	19.28	10.33	5.87	1.91	0.55	776.	5.0	10.5	7.8	3.29	49.36 *
1.500	8,999	22.40	15.38	11.41	6.53	3.88	1.30	0.48	729.	23.2	14.5	10.8	0.88	53.86
1.400	8,999	36.46	25.55	19.68	11.37	6.76	2.25	0.30	360.	31.1	7.0	12.0	2.43	53.44
1.400	8,999	30.93	23.58	18.61	11.77	7.51	2.64	0.25	851.	21.7	7.5	7.1	0.73	56.20
1.300	8,999	26.12	17.92	11.73	6.20	2.77	0.55	0.55	554.	11.9	13.8	39.5	3.01	46.46 *
1.200	8,999	47.79	34.81	27.81	12.97	6.76	2.03	0.59	419.	5.0	7.0	8.5	6.93	46.24 *
1.100	8,999	17.03	12.30	9.85	5.81	3.49	1.33	0.45	1696.	7.0	25.8	6.7	1.47	55.30
1.000	8,999	27.38	19.41	14.26	7.71	4.35	1.56	0.41	785.	5.8	16.3	6.8	1.85	49.36
0.900	8,999	29.73	19.30	13.49	6.48	3.23	1.02	0.47	466.	9.1	14.3	14.7	3.84	46.09
0.800	8,999	25.59	17.95	13.48	7.71	5.18	2.76	1.17	794.	6.3	23.5	2.4	1.35	62.25 *
0.700	8,999	13.93	10.03	7.84	4.77	3.13	1.70	0.88	1771.	10.8	39.2	3.9	1.29	79.09 *
0.600	8,999	16.97	11.26	8.32	4.50	2.56	1.09	0.55	1109.	7.8	37.2	6.4	1.33	50.20
0.500	8,999	16.40	11.74	8.66	5.88	4.24	2.75	1.41	440.	76.5	25.5	2.5	2.47	286.65 *
0.400	8,999	19.94	14.03	10.77	5.80	3.60	2.04	1.07	1038.	6.6	33.3	3.3	3.51	50.40 *
0.300	8,999	20.45	14.22	10.81	6.32	3.95	1.77	0.63	1040.	8.5	24.1	4.1	1.06	62.13
0.200	8,999	22.13	14.44	11.51	5.82	3.43	1.48	0.63	925.	5.0	32.3	4.4	2.96	46.31 *
0.100	8,999	18.47	11.30	7.82	3.47	1.81	0.92	0.50	806.	5.7	65.9	6.6	2.60	50.27 *
0.000	8,999	17.25	11.53	8.14	3.90	1.86	0.74	0.53	783.	17.5	23.1	24.8	7.63	46.41
27.260	8,999	35.20	26.00	18.83	10.02	5.09	1.21	0.46	645.	5.0	9.8	16.7	2.97	45.86 *
27.160	8,999	17.54	12.07	9.35	4.89	2.79	1.15	0.57	1315.	5.0	44.8	5.6	2.20	47.89 *
27.045	8,999	17.54	12.75	9.84	5.95	3.64	1.58	0.62	1516.	7.2	27.8	4.8	0.81	58.03
26.960	8,999	22.47	17.19	13.98	9.74	7.12	4.23	2.09	1235.	20.6	16.2	1.6	0.90	202.14 *
26.860	8,999	22.30	16.49	13.06	7.93	4.91	2.07	0.71	1273.	7.1	17.8	4.3	1.26	60.00
26.760	8,999	23.15	16.33	12.28	7.46	4.87	2.51	1.13	888.	8.5	21.9	2.7	0.54	76.11
26.660	8,999	25.03	18.54	14.64	9.96	7.16	4.32	2.09	455.	67.3	12.2	2.2	3.02	233.08 *
26.560	8,999	20.16	13.60	9.81	5.06	2.80	1.25	0.50	947.	5.0	41.7	5.0	1.60	47.09 *
26.460	8,999	22.04	16.05	11.59	6.99	4.01	1.69	0.72	1086.	5.1	25.7	4.3	0.90	50.63
26.360	8,999	18.81	12.08	8.81	4.62	2.70	1.25	0.54	752.	13.6	26.5	7.1	2.38	48.10
26.260	8,999	17.10	11.59	8.17	3.84	1.98	0.83	0.50	1081.	5.0	63.4	7.4	2.94	46.97 *
26.160	8,999	22.79	17.02	13.05	8.16	5.17	2.22	0.87	1162.	9.7	15.9	4.2	0.51	65.41
26.060	8,999	18.61	12.97	9.07	4.95	2.62	1.06	0.51	1102.	5.0	43.1	6.1	1.07	47.06 *
25.960	8,999	24.60	17.46	12.75	7.72	4.89	2.29	1.23	754.	10.7	17.6	3.3	0.33	65.34
25.860	8,999	25.30	18.46	14.06	8.07	4.86	2.09	0.96	966.	5.0	19.9	3.7	1.59	55.37 *
25.760	8,999	22.62	17.29	12.31	7.39	4.58	2.10	0.92	1091.	5.0	24.9	3.3	1.46	60.24 *
25.660	8,999	20.01	15.66	11.83	8.87	4.59	2.79	1.54	1678.	5.0	26.5	2.6	5.81	46.55 *
25.560	8,999	23.51	17.90	14.97	10.02	7.05	3.93	1.50	1426.	9.4	16.9	1.8	1.33	130.64
25.460	8,999	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	974.	[illegible]	22.8	[illegible]	0.64	113.53 *
25.260	8.999	20.78	14.55	11.52	7.00	5.06	2.71	1.10	844.	20.3	20.4	2.5	1.85	100.66
25.160	8.999	18.93	12.78	8.68	4.75	2.80	1.34	0.52	867.	7.4	37.7	4.2	0.46	52.61
25.060	8.999	16.33	12.23	8.93	6.01	4.05	1.98	0.80	1126.	34.8	21.4	4.1	1.00	63.70
24.960	8.999	17.25	12.83	9.33	6.02	3.90	1.53	0.80	1351.	10.9	26.6	3.6	0.76	73.19
24.859	8.999	14.68	10.73	8.73	5.28	3.50	1.84	0.85	1964.	8.4	37.0	3.7	1.81	84.63 *
24.760	8.999	12.69	8.59	6.25	3.74	2.42	1.18	0.51	1173.	26.1	36.3	6.1	0.56	72.98
24.660	8.999	25.45	18.29	13.60	8.26	5.09	1.88	0.59	805.	18.0	12.2	7.2	0.71	56.18
24.560	8.999	28.44	22.06	17.85	11.99	8.27	3.91	1.34	884.	33.0	9.0	2.8	0.82	77.11
		0	8	12	18	24	36	60						
Mean:		23.32	16.45	12.30	7.02	4.23	1.87	0.77	921.	13.2	25.6	7.0	3.00	56.83
Std. Dev:		6.83	5.25	4.25	2.60	1.78	0.94	0.41	364.	13.9	15.0	5.4	7.48	15.88
Var Coeff(%):		29.30	31.90	34.57	37.11	42.16	50.28	52.87	40.	100.0	58.5	92.1	248.94	27.94

AVG AC. MIX TEMP ≈ 105°

E_{AC} @ 105° ≈ 120,400 PSI

BAD CORRELATION
THIS FILE WAS RUN ON
3 DIFFERENT DAYS WITH
FAIRLY LARGE TEMP. DIFF.
PLUS AC PVMNT IS ONLY
3" THICK. {SOMEWHAT THIN LAYER}
AC TEMP EST. AND/OR
A.C THICKNESS FROM
HISTORY DATA IS
EVIDENTLY WRONG
OR TEMP EST. IS
WRONG

DUE TO CLOSE PROXIMITY
OF STIFF LAYER, THE
TWO SUBGR VALUES
CANNOT BE AVGERAGED,
THEREFORE USE THE
MR CALC. FOR 1ST 36"
OF SUBGR

M_R = 25,600 PSI

$M_{R\,DESIGN}$ = 0.33(25,600)
= 8448

VERY POOR
RESULTS, BUT
IS THE BEST
I CAN GET

DEPTH TO STI[illegible]
LAYER ≈ 4.74

FILE # J:\RI9310\FWD\PRE-RHAB\2P390X2C.FWD

DATE TESTED: 5-11-94 TTI MODULUS ANALYSIS SYSTEM (SUMMARY REPORT) (Version 4.2

District: 2				MODULI RANGE(psi)			
County: 59		Thickness(in)		Minimum	Maximum	Poisson Ratio Values	
Highway/Road:36	Pavement:	3.00	A.C	50,000	3,000,001	H1: u = 0.35	
LOG 703-9.17	Base:	8.00	PCCP	1,000,000	9,500,000	H2: u = 0.15	
	Subbase:	4.00	A.B	5,000	150,000	H3: u = 0.35	
AVG A.C MIX TEMP 94°	Subgrade:	285.00		15,000		H4: u = 0.40	

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (ksi): SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	Absolute ERR/Sens	Dpth to Bedrock
7.100	8,999	10.28	5.98	5.00	4.76	4.43	3.66	2.32	50.	2267.2	150.0	16.7	5.02	300.00 *
7.200	8,999	6.59	4.24	3.93	3.73	3.48	2.90	1.87	76.	6796.7	6.1	20.2	1.13	300.00
7.300	8,999	6.49	5.20	4.84	4.60	4.31	3.73	2.59	141.	6197.5	118.7	13.1	1.26	300.00
7.400	8,999	8.93	5.72	5.42	5.26	4.90	4.18	2.76	56.	6653.1	9.2	12.0	0.67	300.00
7.517	8,999	7.59	6.60	6.28	5.98	5.59	4.71	3.11	226.	4554.8	62.4	10.3	0.39	300.00
7.600	8,999	6.60	5.77	5.45	5.04	4.63	3.70	2.08	329.	3083.0	15.0	15.4	0.38	300.00
7.700	8,999	6.71	5.70	5.02	4.70	4.36	3.56	2.27	180.	3499.4	14.6	16.5	2.02	300.00
7.800	8,999	6.28	4.11	3.84	3.62	3.36	2.73	1.71	85.	6181.3	6.9	22.0	0.81	300.00
7.900	8,999	7.77	5.38	4.95	4.73	4.38	3.59	2.24	77.	4536.0	86.9	15.0	0.98	300.00
8.000	8,999	9.38	6.41	5.62	5.43	5.06	4.21	2.70	58.	4069.2	15.7	13.4	2.19	300.00
8.100	8,999	7.94	7.11	6.44	5.96	5.38	4.23	2.63	604.	1000.0	109.4	13.5	0.83	300.00 *
		0	8	12	18	24	36	60						
Mean:		7.69	5.66	5.16	4.89	4.53	3.75	2.39	171.	4439.8	54.1	15.3	1.42	300.00
Std. Dev:		1.34	0.92	0.82	0.77	0.70	0.58	0.41	168.	1897.7	53.6	3.5	1.33	55.25
Var Coeff(%):		17.44	16.18	15.86	15.71	15.37	15.53	17.36	98.	42.7	99.0	22.6	93.26	18.42

Goo

EQA

GOOD PCCP GOOD BASE GOOD MR

GOOD AC

$E_{PCC} = 4,439,800$

$Sc' = 43.5(4.4398) + 488.5$

$Sc' = 682$

$M_{r\,DYN} = 15,300$

$M_{r\,DES} = 15,300(0.33)$

$= 5049$

$K_{STAT} = \frac{5049}{19.4}$

$K_{STAT} = 260$

12345X@PJL ENTER LANGUAGE = PCL

FILE # J:\RI9310\ FWD\ PRE_RHAB\ 2P390X2C.FWD

DATE TESTED: 5-11-94 TTI MODULUS ANALYSIS SYSTEM (SUMMARY REPORT) (Version 4.2)

District: 2
County: 59
Highway/Road: 36

LOG 0.00 - LOG 7.03

AVG A.C. MIX TEMP 84°

		Thickness(in)	MODULI RANGE(psi) Minimum	Maximum	Poisson Ratio Values
Pavement:	A.C.	3.50	50,000	3,000,001	H1: u = 0.35
Base:	PCCP	8.00	1,000,000	9,500,000	H2: u = 0.15
Subbase:	AGGR. BASE	4.00	5,000	150,000	H3: u = 0.35
Subgrade:		284.50	23,500		H4: u = 0.40

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (ksi): SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	Absolute ERR/Sens	Dpth to Bedrock
0.000	8,999	2.56	2.45	2.30	2.13	1.92	1.54	0.89	3000.	4126.4	13.2	37.0	1.24	300.00 *
0.100	8,999	4.43	3.69	3.48	3.26	3.00	2.42	1.45	369.	5509.3	13.7	23.6	0.45	300.00
0.200	8,999	3.89	3.58	3.43	3.19	2.92	2.35	1.51	1555.	3710.9	6.7	24.6	0.53	300.00
0.300	8,999	5.19	4.92	4.73	4.34	3.95	3.12	1.65	1862.	1783.0	10.8	17.2	1.56	300.00
0.400	8,999	3.54	3.39	3.30	3.05	2.77	2.19	1.26	3000.	2935.4	7.9	24.7	1.93	300.00 *
0.500	8,999	5.63	5.53	4.27	2.37	1.30	0.61	0.22	90.	2178.1	7.3	72.6	37.77	48.42 *
0.600	8,999	3.89	3.62	3.49	3.21	2.88	2.25	1.26	2288.	2285.1	7.7	25.7	1.41	300.00
0.704	8,999	5.15	4.91	4.76	4.43	4.12	3.38	2.18	1767.	2824.0	34.3	14.2	1.14	300.00
0.800	8,999	3.84	3.76	3.64	3.40	3.16	2.59	1.55	2979.	3599.0	51.0	17.8	1.82	300.00
0.902	8,999	6.41	5.92	5.60	5.25	4.90	4.03	2.45	797.	2804.6	28.6	12.7	0.54	300.00
1.000	8,999	3.94	3.57	3.41	3.11	2.83	2.24	1.28	1504.	2736.0	11.8	26.1	0.39	300.00
1.200	8,999	2.92	2.70	2.56	2.39	2.15	1.74	1.07	2661.	3722.6	11.6	33.0	0.50	300.00
1.300	8,999	3.35	3.09	2.96	2.72	2.48	1.92	1.02	2555.	2521.2	26.9	28.1	1.32	300.00
1.400	8,999	4.54	3.56	3.30	3.05	2.76	2.17	1.18	251.	4502.1	18.8	27.9	0.50	300.00
1.502	8,999	5.66	4.83	4.51	4.20	3.90	3.18	2.08	317.	4191.8	18.5	17.5	0.74	300.00
1.600	8,999	5.76	4.45	4.11	3.76	3.37	2.66	1.52	188.	3240.6	24.3	22.8	0.70	300.00
1.700	8,999	3.58	3.27	3.10	2.89	2.66	2.13	1.23	2729.	2758.1	8.0	27.0	0.60	300.00
1.800	8,999	6.37	5.87	5.69	5.27	4.80	3.83	2.18	1238.	1747.7	9.9	14.0	1.08	300.00
1.900	8,999	4.09	3.71	3.52	3.23	2.95	2.37	1.43	2112.	2111.7	22.2	23.3	0.22	300.00
2.000	8,999	4.83	3.90	3.74	3.50	3.21	2.66	1.66	266.	6504.7	8.1	21.2	0.13	300.00
2.100	8,999	2.42	2.15	2.05	1.84	1.62	1.21	0.63	1931.	3784.2	6.4	63.5	0.87	300.00
2.203	8,999	6.68	5.91	5.45	4.81	4.18	2.98	1.23	607.	1000.0	5.0	23.0	1.28	165.21 *
2.300	8,999	4.54	4.21	4.01	3.71	3.44	2.77	1.60	1302.	3192.3	12.0	19.7	0.61	300.00
2.400	8,999	5.29	4.39	4.20	3.86	3.55	2.80	1.55	324.	3602.2	61.3	19.9	0.42	300.00
2.500	8,999	4.61	3.93	3.53	3.32	3.00	2.34	1.27	416.	3157.1	67.2	24.8	1.03	300.00
2.601	8,999	7.47	6.29	5.91	5.49	4.92	3.91	2.29	268.	1881.1	101.4	14.5	0.28	300.00
2.700	8,999	4.66	3.07	2.70	2.36	1.98	1.29	0.57	164.	1973.3	13.7	55.7	1.09	195.10
2.800	8,999	3.58	3.14	2.98	2.75	2.50	1.96	1.13	830.	4423.2	10.7	31.1	0.38	300.00
2.900	8,999	4.62	4.17	4.03	3.73	3.43	2.75	1.56	981.	3638.9	5.0	21.8	0.55	300.00 *
3.000	8,999	3.97	3.72	3.62	3.36	3.06	2.46	1.46	2135.	3123.2	9.5	21.8	1.25	300.00
3.100	8,999	5.37	4.74	4.59	4.30	3.94	3.24	2.03	525.	4287.7	14.7	16.5	0.35	300.00
3.200	8,999	4.68	4.33	4.19	3.96	3.66	3.03	1.91	1204.	4227.3	42.9	16.2	0.62	300.00
3.300	8,999	4.89	4.21	4.05	3.80	3.52	2.94	1.88	412.	5744.3	49.4	17.4	0.09	300.00
3.400	8,999	5.73	5.29	5.06	4.70	4.32	3.48	2.12	1074.	2481.6	7.0	16.0	0.56	300.00
3.500	8,999	4.77	4.34	4.16	3.79	3.45	2.71	1.51	1092.	2384.9	14.6	20.9	0.74	300.00
3.800	8,999	13.30	12.56	9.56	7.79	6.87	5.12	2.85	82.	1000.0	5.0	12.3	7.22	300.00 *
3.900	8,999	5.15	4.05	3.85	3.53	3.21	2.47	1.46	246.	3467.1	52.7	23.3	0.54	300.00
4.004	8,999	4.80	4.23	3.99	3.68	3.35	2.66	1.64	631.	2996.2	46.0	21.2	0.26	300.00
4.100	8,999	3.71	3.21	3.11	2.89	2.66	2.13	1.28	641.	5875.1	23.4	25.6	0.64	300.00
4.205	8,999	3.70	3.30	3.27	3.00	2.74	2.13	1.12	1235.	4096.7	6.0	28.6	1.61	300.00
4.300	8,999	2.47	2.12	2.10	1.95	1.72	1.30	0.64	1335.	5992.9	5.6	56.2	1.86	288.79 *
4.400	8,999	4.06	3.89	3.85	3.61	3.31	2.76	1.66	3000.	3804.1	5.0	18.3	1.42	300.00 *
4.500	8,999	4.03	3.92	3.88	3.66	3.42	2.84	1.80	2888.	4799.7	11.1	15.7	1.75	300.00
4.600	8,999	4.63	4.17	4.10	3.87	3.62	3.04	1.93	831.	6171.4	34.8	15.7	0.59	300.00
4.700	8,999	2.68	2.08	2.01	1.83	1.60	1.13	0.39	541.	4468.8	45.9	53.5	2.05	125.77
4.800	8,999	3.37	3.12	3.00	2.78	2.53	1.97	1.02	2764.	2764.0	8.7	28.9	1.35	300.00
4.901	8,999	5.28	4.51	4.20	3.90	3.61	2.99	1.91	319.	5011.3	7.3	19.5	0.91	300.00

5.200	8,999	5.44	4.63	4.45	4.13	3.61	3.10	1.92	360.	4208.4	48.6	17.3	0.19	300.00	
5.300	8,999	6.83	5.85	5.75	5.39	4.96	4.00	2.37	321.	3738.6	13.1	13.2	1.03	300.00	
5.400	8,999	2.82	1.97	1.85	1.76	1.60	1.23	0.63	280.	9500.0	28.0	48.7	1.18	300.00	!
5.500	8,999	5.23	4.74	4.53	4.41	4.15	3.38	2.00	691.	5557.5	17.2	14.2	1.34	300.00	
5.600	8,999	5.60	4.25	3.95	3.62	3.29	2.58	1.39	182.	3446.1	56.2	22.8	0.56	300.00	
5.700	8,999	4.46	3.74	3.69	3.47	3.16	2.52	1.39	449.	5257.2	48.0	20.9	1.29	300.00	
5.800	8,999	4.66	4.24	4.12	3.86	3.62	3.05	1.96	898.	5473.0	38.3	16.0	0.23	300.00	
5.904	8,999	5.14	4.83	4.71	4.42	4.14	3.48	2.23	1484.	3993.0	22.2	13.6	0.55	300.00	
6.000	8,999	4.68	4.32	4.22	3.95	3.70	3.11	1.98	1459.	4455.6	15.8	15.7	0.39	300.00	
6.103	8,999	4.71	4.20	4.07	3.82	3.57	2.94	1.89	666.	5570.1	9.3	17.9	0.38	300.00	
6.200	8,999	2.69	2.40	2.32	2.11	1.93	1.48	0.76	1504.	5093.0	7.7	44.1	1.01	300.00	
6.302	8,999	5.21	4.76	4.62	4.41	4.16	3.50	2.30	830.	5541.1	84.8	13.1	0.57	300.00	
6.400	8,999	3.81	3.24	3.04	2.92	2.69	2.23	1.36	442.	7803.5	75.8	22.9	0.72	300.00	
6.500	8,999	6.72	5.00	4.96	4.67	4.32	3.51	2.11	144.	4927.9	88.9	14.4	1.14	300.00	
6.600	8,999	14.92	9.53	8.37	7.43	6.47	4.57	2.41	50.	1000.0	5.0	14.7	2.70	300.00	!
6.700	8,999	6.70	3.88	3.01	2.60	2.28	1.72	0.94	79.	1210.1	150.0	40.3	4.68	300.00	!
6.910	8,999	7.23	5.21	4.98	4.68	4.34	3.60	2.31	112.	4897.8	103.3	14.4	0.24	300.00	
		0	8	12	18	24	36	60							
Mean:		4.93	4.25	4.00	3.67	3.34	2.66	1.56	1080	3927.6	28.7	24.4	1.59	300.00	
Std. Dev:		2.02	1.57	1.28	1.13	1.04	0.84	0.55	906.	1657.6	29.1	12.8	4.64	287.91	
Var Coeff(%):		40.87	37.03	32.08	30.73	31.14	31.63	35.23	84.	42.2	100.0	52.6	291.15	95.97	

E_{AC} = TOO HIGH

EITHER TEMP. INFO IS WRONG OR A.C. THICKNESS IS WRONG

LOW AGGR BASE

GOOD M_R

FAIR TO R ERROR

$M_{r_{DYN}} = 24,400$

$M_{r_{DES}} = 0.33(24,400)$

$= 8052$

$K_{STAT} = \dfrac{8052}{19.4}$

$K_{STAT} = 415$

OK

$E_{PCC} = 3,927,600$

$Sc' = 43.5(3.9276) + 488.5$

$Sc' = 659$

FILE # J:\RT9310\1994\9P307X2C.FWD

DATE TESTED: 4-13-94

TTI MODULUS ANALYSIS SYSTEM (SUMMARY REPORT) (Version 4.2)

District: 9			MODULI RANGE(psi)		
County: 107		Thickness(in)	Minimum	Maximum	Poisson Ratio Values
Highway/Road:60	Pavement: PCCP	8.00	1,000,000	8,999,999	H1: u = 0.15
5 DAY AVG AIR TEMP = 48°	Base:	4.00	5,000	150,000	H2: u = 0.35
AVG PVMNT SURFACE TEMP = 68°	Subbase:	0.00	0	0	H3: u = 0.15
	Subgrade:	236.00	15,000		H4: u = 0.40

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (ksi): SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	Absolute ERR/Sens	Dpth to Bedrock
13.206	8,999	8.84	8.58	8.36	7.85	7.36	6.31	4.04	5138.	20.6	0.0	6.7	0.29	300.00
13.311	8,999	4.38	4.21	4.02	3.71	3.39	2.82	1.74	7025.	28.5	0.0	17.7	0.50	300.00
13.414	8,999	5.71	5.52	5.35	5.02	4.66	3.99	2.60	7211.	38.0	0.0	11.0	0.29	300.00
13.506	8.999	6.21	5.99	5.82	5.42	5.06	4.26	2.61	6281.	30.7	0.0	10.5	0.34	300.00
13.611	8,999	4.33	4.07	3.93	3.50	3.00	2.19	1.03	4023.	8.6	0.0	28.6	1.94	103.17 *
13.706	8,999	5.10	4.90	4.72	4.39	4.02	3.33	2.00	6437.	23.7	0.0	14.6	0.41	300.00
13.811	8,999	5.23	4.94	4.76	4.39	4.05	3.33	2.08	5905.	24.2	0.0	15.0	0.22	300.00
13.918	8,999	4.79	4.61	4.41	4.19	3.84	3.28	2.06	7945.	63.5	0.0	13.8	0.47	300.00
14.014	8,999	4.94	4.78	4.62	4.27	3.99	3.41	2.28	7866.	54.4	0.0	13.2	0.59	300.00
14.133	8,999	6.22	6.01	5.85	5.49	5.17	4.44	2.96	7370.	30.0	0.0	9.5	0.21	300.00
14.204	8,999	6.14	5.94	5.72	5.36	4.96	4.21	2.70	6301.	30.8	0.0	10.7	0.29	300.00
14.313	8,999	4.60	4.37	4.21	3.84	3.55	2.89	1.72	6341.	23.4	0.0	17.7	0.37	209.36
14.408	8,999	4.13	3.95	3.83	3.54	3.27	2.71	1.67	8226.	25.6	0.0	17.7	0.28	300.00
14.514	8,999	5.94	5.78	5.56	5.16	4.81	4.05	2.51	6084.	79.5	0.0	11.2	0.47	300.00
14.606	8.999	4.44	4.22	4.06	3.75	3.45	2.87	1.52	7213.	27.3	0.0	17.2	0.24	127.18
14.711	8,999	4.90	4.75	4.62	4.25	3.96	3.32	2.15	7547.	17.7	0.0	14.1	0.57	300.00
14.804	8.999	4.75	4.57	4.43	4.12	3.85	3.31	2.05	8551.	57.1	0.0	13.4	0.43	300.00
14.908	8,999	5.20	4.99	4.80	4.42	4.07	3.37	2.03	6115.	24.1	0.0	14.6	0.37	300.00
15.012	8,999	4.41	4.18	4.03	3.72	3.41	2.82	1.73	7012.	28.5	0.0	17.7	0.21	300.00
15.116	8,999	5.10	4.89	4.73	4.41	4.11	3.31	1.81	6483.	23.2	0.0	14.4	0.86	157.66
15.209	8,999	5.21	4.96	4.72	4.34	3.97	3.29	1.91	5614.	23.5	0.0	15.6	0.44	187.72
15.313	8,999	4.76	4.44	4.19	3.79	3.47	2.88	1.84	5300.	53.8	0.0	18.6	1.16	300.00
0.012	8,999	5.18	4.92	4.77	4.36	4.01	3.31	1.89	5942.	24.4	0.0	15.1	0.37	176.62
0.116	8,999	6.58	6.26	6.04	5.55	5.06	4.08	2.12	4127.	53.8	0.0	12.3	0.55	140.12
0.209	8,999	5.75	5.50	5.30	4.90	4.50	3.74	2.34	5365.	87.9	0.0	12.9	0.27	300.00
0.313	8,999	4.31	4.14	3.96	3.59	3.28	2.62	1.46	6329.	6.5	0.0	21.7	0.69	156.98 *
0.405	8,999	5.14	4.97	4.78	4.44	4.13	3.48	2.23	7157.	22.6	0.0	13.4	0.38	300.00
0.509	8,999	4.69	4.52	4.32	3.92	3.58	2.91	1.74	6053.	5.9	0.0	19.3	0.69	215.00
0.614	8,999	5.37	5.18	4.98	4.56	4.16	3.39	1.95	5373.	23.2	0.0	14.9	0.64	189.74
0.706	8,999	4.72	4.50	4.30	3.98	3.66	3.04	1.91	6703.	24.1	0.0	16.4	0.25	300.00
0.810	8,999	4.76	4.51	4.36	3.98	3.63	2.99	1.82	6062.	23.5	0.0	17.2	0.44	300.00
0.903	8,999	6.03	5.87	5.64	5.22	4.83	3.86	2.13	4806.	87.2	0.0	12.4	1.24	175.00
1.018	8,999	6.12	5.89	5.70	5.28	4.88	4.10	2.58	5524.	97.0	0.0	11.3	0.35	300.00
1.111	8,999	5.60	5.39	5.21	4.78	4.39	3.53	2.11	4794.	138.5	0.0	13.9	0.93	245.07 *
1.204	8,999	5.61	5.45	5.28	4.91	4.56	3.87	2.50	6955.	42.0	0.0	11.6	0.48	300.00
1.308	8,999	5.06	4.88	4.73	4.37	4.08	3.40	2.14	7222.	23.8	0.0	13.7	0.49	300.00
1.412	8,999	4.50	4.20	3.95	3.52	3.16	2.41	1.21	4288.	17.5	0.0	24.4	0.51	117.81
1.504	8,999	5.36	5.19	5.01	4.67	4.35	3.70	2.40	7274.	44.8	0.0	12.1	0.38	300.00
1.597	8,999	5.32	4.88	4.65	4.20	3.84	3.10	1.90	4585.	17.0	0.0	18.0	0.85	300.00
1.701	8,999	5.62	5.46	5.29	4.95	4.59	3.90	2.52	7036.	42.8	0.0	11.4	0.41	300.00
1.805	8,999	5.52	5.36	5.24	4.90	4.58	3.91	2.59	7946.	41.9	0.0	10.9	0.42	300.00
1.908	8,999	5.24	5.07	4.86	4.52	4.17	3.52	2.21	6781.	21.9	0.0	13.5	0.46	300.00
2.012	8,999	4.77	4.58	4.40	4.11	3.82	3.18	1.98	7588.	21.5	0.0	14.8	0.22	300.00
2.116	8,999	5.69	5.54	5.41	5.16	4.81	3.71	2.03	5779.	92.5	0.0	12.0	2.54	179.97
2.209	8,999	5.26	5.09	4.95	4.57	4.25	3.60	2.32	7169.	54.2	0.0	12.6	0.53	300.00
2.312	8,999	4.97	4.66	4.43	3.99	3.59	2.71	1.24	4087.	16.1	0.0	21.1	0.91	100.00
10.408	8,999	4.66	4.48	4.30	3.91	3.60	2.94	1.70	6208.	23.2	0.0	17.4	0.57	182.41
10.512	8,999	4.66	4.46	4.29	3.92	3.64	2.99	1.85	6660.	22.2	0.0	16.7	0.46	300.00
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

10.809	8,999	4.62	4.47	4.32	4.05	3.77	3.22	2.03	8853.	70.6	0.0	13.6	0.26	300.00
10.913	8.999	5.32	5.12	4.92	4.57	4.20	3.47	2.06	6168.	24.3	0.0	13.9	0.38	216.90
11.005	8,999	4.31	4.09	3.92	3.55	3.21	2.58	1.48	5854.	20.3	0.0	20.9	0.50	172.72
11.121	8,999	4.68	4.43	4.25	3.87	3.53	2.82	1.61	5558.	18.7	0.0	18.9	0.38	177.93
11.214	8,999	4.58	4.36	4.22	3.84	3.53	2.87	1.72	6275.	23.3	0.0	17.8	0.44	216.46
11.306	8,999	6.65	6.50	6.34	5.96	5.65	4.87	3.26	7475.	31.8	0.0	8.3	0.48	300.00
11.410	8,999	6.48	6.27	6.02	5.55	5.14	4.24	2.58	4700.	112.2	0.0	11.3	0.57	300.00
11.503	8,999	5.86	5.65	5.46	5.09	4.77	4.11	2.76	7146.	58.1	0.0	10.6	0.42	300.00
11.607	8,999	4.08	3.80	3.62	3.33	3.06	2.53	1.62	7064.	27.6	0.0	20.6	0.75	300.00
11.712	8,999	4.48	4.26	4.07	3.74	3.42	2.79	1.69	6364.	27.5	0.0	18.4	0.23	300.00
11.804	8,999	5.44	5.15	4.94	4.54	4.13	3.29	1.87	5088.	5.2	0.0	17.2	0.42	186.99 !
11.908	8,999	6.16	6.06	5.93	5.67	5.38	4.76	3.35	8450.	49.2	0.0	8.5	1.10	300.00 !
12.117	8,999	4.19	3.96	3.80	3.49	3.18	2.56	1.48	6741.	6.7	0.0	22.1	0.20	178.09
12.210	8,999	5.38	4.98	4.75	4.32	3.88	3.09	1.73	4288.	16.4	0.0	18.1	0.29	170.17
12.303	8,999	5.74	5.56	5.44	5.08	4.77	4.09	2.71	7763.	38.2	0.0	10.4	0.33	300.00
12.408	8,999	4.79	4.60	4.36	3.99	3.64	2.94	1.82	5802.	5.8	0.0	19.3	0.43	300.00 !
12.512	8,999	5.10	4.73	4.41	3.92	3.50	2.73	1.51	3712.	16.7	0.0	21.9	0.59	160.24
12.604	8,999	6.29	6.11	5.89	5.48	5.10	4.29	2.66	5991.	30.5	0.0	10.6	0.43	300.00
12.709	8,999	5.21	5.14	4.99	4.66	4.35	3.69	2.31	7950.	68.7	0.0	11.7	0.79	300.00
12.813	8,999	5.16	4.95	4.83	4.43	4.09	3.38	2.05	6399.	23.9	0.0	14.3	0.49	300.00
12.905	8,999	6.02	5.72	5.51	5.06	4.63	3.81	2.26	4708.	84.9	0.0	13.0	0.29	227.60
13.009	8,999	4.72	4.42	4.22	3.81	3.30	2.61	1.65	4282.	17.3	0.0	22.3	0.92	300.00
13.113	8,999	6.67	6.53	6.39	5.96	5.60	4.85	3.23	7149.	27.9	0.0	8.5	0.57	300.00
		0	8	12	18	24	36	60						
Mean:		5.22	5.01	4.83	4.46	4.11	3.41	2.08	6326.	36.6	0.0	15.3	0.55	248.09
Std. Dev:		0.81	0.82	0.82	0.79	0.77	0.71	0.53	1243.	26.6	0.0	4.4	0.37	90.99
Var Coeff(%):		15.56	16.38	16.89	17.83	18.84	20.87	25.61	20.	72.8	0.0	29.1	68.03	36.68

GOOD
E_{PCC}

GOOD RESULTS

$$S_c' = 43.5\left(\frac{E_{pcc}}{10^6}\right) + 488.5$$
$$= 43.5(6.326) + 488.5$$
$$= 763 \text{ psi}$$

$$m_{r_{DES}} = 0.33(15{,}300)$$
$$= 5049$$

$$K_{STAT} = \frac{m_{r_{DES}}}{19.4} = \frac{5049}{19.4} = 260 \text{ pci}$$

Appendix F depicts examples of manual calculations to determine overlay thickness using NDT deflection data. The AASHTO Design Guide Chapter 5 procedure was employed along with the DARWin program. In this appendix there are examples of AC overlay of AC pavements, AC overlay of AC/PCC pavements, and AC overlay of PCC pavements. The procedural steps and equations follow that in Chapter 5 of the 1993 AASHTO Design Guide.

APPENDIX F

1993 AASHTO Pavement Design

DARWin(tm) Pavement Design System

A Proprietary AASHTOWARE(tm)
Computer Software Product

MISSOURI HIGHWAY AND TRANSPORTATION DEPARTMENT
1511 MISSOURI BOULEVARD, PO BOX 270
JEFFERSON CITY, MO. 65102
RONALD L. NETEMEYER

Overlay Design Module

AC Overlay of AC Pavement

DIST. 8 POLK CO. RTE 32 JOB # 8-U-448 LOG 9.47 - LOG 10.20 CITY OF BOLIVAR DATE TESTED: 8-26-93 BEFORE OVERLAY FILE# J:\RI9310\DW\8U448A

Overlay Design Module Data

Structural Number for Future Traffic:	4.38
Effective Structural Number of Existing Pavement--Non-Destructive Method:	2.05
Calculated Overlay Structural Number:	2.33

Structural Number for Future Traffic

Future 18-kips ESALs Over Design Period:	2,098,750
Initial Serviceability:	4.2
Terminal Serviceability:	2.5
Reliability Level (%):	90
Overall Standard Deviation:	.49
Subgrade Resilient Modulus (PSI):	5,798
Calculated Structural Number for Future Traffic:	4.38

Effective Pavement Structural Number--Non-Destructive Method

Total Thickness of All Existing Pavement Layers (in):	11
Backcalculated Effective Pavement Modulus:	72,211
Calculated Effective Pavement Structural Number:	2.05

Specified Layer Design

Layer	Material Description	Struct. Coef. (Ai)	Drain. Coef. (Mi)	Thickness (Di) (in)	Width (ft)	Calculated SN
1	ASPHALT CONC.	.44	1	5.29	-	2.33
Total	-	-	-	5.29	-	2.33

Effective Roadbed Soil Resilient Modulus Data

Period	Modulus	Period	Modulus	Period	Modulus	Period	Modulus
1	5,798	7	-	13	-	19	-
2	-	8	-	14	-	20	-
3	-	9	-	15	-	21	-
4	-	10	-	16	-	22	-
5	-	11	-	17	-	23	-
6	-	12	-	18	-	24	-

Calculated Effective Modulus: 5,798

Point-by-Point Backcalculation

FWD Load (lbs):	9,000
Load Plate Radius (in):	5.9
Pavement Temperature:	100

Sensor Number	Location (in)	Deflection (mils)
1	-	24.9
2	12	11.68
3	18	6.83
4	24	4.28
5	36	2.11
6	60	.99

Existing AC Thickness:	6
Total Pavement Thickness:	11
Stress Dependency Correction Factor:	.33
Base Type:	Granular
Calculated Subgrade Resilient Modulus (psi):	5,797.95
Calculated Effective Pavement Modulus (psi):	72,210.83

District 8 Polk County Route 32 Location: log mile 11.10-12.15 City of Bolivar

AC Overlay of AC Pavement (using NDT deflection results)

Step 1: Existing Pavement Design
6" AC, 5" aggregate base
D=11"

Step 2: Traffic Analysis
From Design: construction year (1992) = 450 flexible ESAL/day
design year (2012) = 700 flexible ESAL/day
Average through 20 year design life = 575 flexible ESAL/day

Step 3: Condition Survey
Not available

Step 4: Deflection Testing

r = 1.5 D = 1.5(11") = 16.5"
use r = 18", d_{18} = 6.83 mils

From NDT
d_0 = 24.90 mils
d_8 = 16.85 mils
d_{12} = 11.68 mils
d_{18} = 6.83 mils
d_{24} = 4.28 mils
d_{36} = 2.11 mils
d_{60} = 0.99 mils
ambient air temperature 91-96 degrees F
surface temperature 105-154 degrees F

1)
$$M_r = \frac{(0.24)P}{(D_r)r} = \frac{(0.24)(9000)}{(0.00683)(18)}$$
$$M_r = 17{,}570\ psi$$

2) Temperature of AC mix estimated from 5 day average + pavement surface temperature ~ 100 degrees F from Figure 5.6, Table III-99 with estimated AC temperature at 100 degrees and AC thickness of 6", TAF_{68} = 0.75

3) Calculate Effective Modulus of Pavement

$$(0.75)(0.02490) = 1.5(82.30)(5.9)\left[\frac{1}{17{,}570\sqrt{1+\left(\frac{11}{5.9}\sqrt[3]{\frac{E_p}{17{,}570}}\right)^2}} + \frac{\left(1-\frac{1}{\sqrt{1+\left(\frac{11}{5.9}\right)^2}}\right)}{E_p}\right]$$

$$0.018675 = \frac{0.04145}{\sqrt{1+\left(1.864\sqrt[3]{\frac{E_p}{17{,}570}}\right)^2}} + \frac{384.09}{E_p}$$

by trial and error.

$E_p = 75{,}000 \quad = 0.01814$

$E_p = 70{,}000 \quad = 0.01877$

use $E_p \sim 71{,}000$ *psi*

check a_e

$$\frac{E_p}{M_r} = \frac{71{,}000}{17{,}570} = 4.00$$

$$a_e = \sqrt{(5.9)^2 + \left(11\sqrt[3]{4.00}\right)^2} = 18.43$$

$r >= 0.7a_e$

$18 >= 12.90 \quad OK$

Step 5: **Coring and Materials Testing**

Not available

Step 6:

1) Effective design subgrade M_r
$M_{r_{design}} = 0.33(17,570) = 5798$ psi

2) Design PSI loss
change in PSI = 4.2-2.5 = 1.7

3) Overlay design reliability
R = 90%

4) Overall standard deviation
$S_0 = 0.49$

5) $W_{18} = D_D * D_L * w_{18}$
$W_{18} = (0.50) * (1) * (575 \text{ ESALS/day} * 365 \text{ day/year} * 20 \text{ year})$
$W_{18} = 2,098,750$ ESALS

from nomograph on page II-32: $SN_f = 4.40$

Step 7:Determine Effective Structural Number (SN_{eff})

$$SN_{eff} = 0.0045(11)\sqrt[3]{71,000}$$
$$SN_{eff} = 2.05$$

Step 8:Determine Overlay Thickness

$SN_{OL} = SN_f - SN_{eff}$
$SN_{OL} = 4.40-2.05 = 2.35$

$SN_{OL} = a_{OL} * D_{OL} * M_{OL}$
$2.35 = (0.44) * D_{OL} * (1)$
$D_{OL} = 5.34"$

Use 5.50"

1993 AASHTO Pavement Design

DARWin(tm) Pavement Design System

A Proprietary AASHTOWARE(tm)
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MISSOURI HIGHWAY AND TRANSPORTATION DEPARTMENT
1511 MISSOURI BOULEVARD, PO BOX 270
JEFFERSON CITY, MO. 65102
RONALD L. NETEMEYER

Overlay Design Module

AC Overlay of AC/PCC Pavement

DISTRICT 2 LIVINGSTON CO. RTE. 36 LOG MILE 7.03 - 9.17 JOB # 2P390
DATE TESTED: 10-21-93 BEFORE OVERLAY FILE# J:\RI9310\DW\2P390A

Overlay Design Module Data

Pavement Thickness for Future Traffic:	9.59
Effective Thickness of Existing Pavement-- Condition Survey Method:	8.63
Calculated Overlay Thickness:	2.00

Thickness for Future Traffic

Future 18-kip ESALs Over Design period:	4,516,875
Initial Serviceability:	4.5
Terminal Serviceability:	2.5
PCC Modulus of Rupture (psi):	631
PCC Elastic Modulus (psi):	3,274,739
Static k-value (psi/in):	129.5
Reliability Level (%):	90
Overall Standard Deviation:	.39
Load Transfer Factor, J:	3.5
Overall Drainage Coefficient, Cd:	1
Calculated Thickness for Future Traffic (in):	9.59

Effective Pavement Thickness--Condition Survey Method

Existing PCC Thickness (in):	8
Existing AC Thickness (in):	3
Durability Adjustment Factor:	.99
Fatigue Damage Adjustment Factor:	
AC Quality Adjustment Factor:	.9
No. of Unrepaired Deteriorated Cracks/mile:	29
No. of Unrepaired Punchouts/mile:	0
No. of Expansion Joints, Exceptionally Wide Joints or AC Full Depth Patches/mile:	0
Calculated Joints and Cracks Adjustment Factor:	.92
Calculated Effective Pavement Thickness:	8.63

Point-by-Point Backcalculation

FWD Load (lbs):	9,000
Load Plate Radius (in):	5.9
Pavement Temperature:	79

Sensor Number	Location (in)	Deflection (mils)
1	0	5.96
2	12	4.8
3	24	4.07
4	36	3.34

Existing AC Thickness:	3
Existing PCC Thickness (in):	8
AC/PCC Interface Condition:	Bonded
Calculated AC Elastic Modulus (psi):	511,998.41
Calculated PCC Resilient Modulus (psi):	630.95
Calculated PCC Elastic Modulus (psi):	3,274,738.79
Calculated Dynamic k-value (psi/in):	259.01
Calculated Slab Bending or AC Compression Factor:	1.24

District 2 Livingston County Route 36 Location: log mile 7.03-9.27

AC Overlay of AC/PCCP (using NDT deflection results)

Step 1: Existing Pavement Design

3" AC, 8" PCCP, 4" aggregate base

Step 2: Traffic Analysis

From Design: construction year (1994) = 2,250 rigid ESALS/day both directions

design year (2004) = 2,700 rigid ESALS/day both directions

Average through 10 year design life = 2,475 rigid ESALS/day both directions

w_{18} = 2,475 ESALS/day * 365 day/year * 10 year

w_{18} = 9,033,750 ESALS

Step 3: Condition Survey

Not available

Step 4: Deflection testing

From NDT

d_0 = 5.96 mils

d_{12} = 4.80 mils

d_{24} = 4.07 mils

d_{36} = 3.34 mils

date tested: 10-25-93

1) Temperature of AC mix estimated from 5 day average + pavement surface temperature. Temperature of AC mix ~ 79° F

2) Elastic Modulus of AC estimated from temperature of AC mix and Asphalt Institute equation. E_{ac} ~ 460,000

3) Effective Dynamic K_{dyn}

$$d_{0_{COMPRESSION\ OF\ AC}} = -0.0000328 + 121.5006\left(\frac{3.0}{460{,}000}\right)^{1.0798}$$

$$d_{0_{COMPRESSION\ OF\ AC}} = 0.00027\ inches = 0.27\ mil$$

$$d_{0_{TOTAL}} = d_{0_{COMPRESSION\ OF\ AC}} + d_{0_{COMPRESSION\ OF\ PCC}}$$

$$5.96 = 0.27 + d_{0_{COMPRESSION\ OF\ PCC}}$$

$$d_{0_{COMPRESSION\ OF\ PCC}} = 5.69\ mils$$

$$AREA = 6\left[1 + 2\left(\frac{4.80}{5.69}\right) + 2\left(\frac{4.07}{5.69}\right) + \left(\frac{3.34}{5.69}\right)\right] = 27.23$$

From figure 5.10, page III-118
with area = 27.23 and d_{0pcc} = 5.69 mils, K_{dyn} = 320 pci

4) Effective Static K_{stat}

K_{stat} = ½ K_{dyn}
K_{stat} = 160 pci

5) Elastic Modulus of PCC slab (E)

From figure 5.11 with area = 27.23 and K_{dyn} = 320 pci
$ED^3 = 1.50*10^9$ psi
$E\,(8)^3 = 1.50*10^9$ psi
E = 2,929,688 psi

6) Joint Load Transfer (not available by NDT)

Assumed value of J ~ 3.5 for LT = 50-70%

Step 5: Coring and Materials Testing
Not available

Step 6: Determination of Required Slab Thickness for Future Traffic D_f

1a) Effective Static K_{stat}
$K_{stat} = 160$ pci

2) Design PSI loss
change in PSI = $P_0 - P_1 = 4.5-2.5 = 2.0$

3) Load Transfer of Existing PCC slab
$J \sim 3.5$

4b) PCC Modulus of Rupture
$S_{c'} = 43.5\ (2.930) + 488.5$
$S_{c'} = 616$ psi

6) Loss of Support
LS = 0

7) Overlay Design Reliability
R = 90%

8) Overall Standard Deviation
$S_0 = 0.39$

9) Coefficient of Drainage
$C_d = 1$

10) Estimated ESALS over design life

$W_{18} = D_D * D_L * w_{18}$
$W_{18} = (0.50) * (1) * 9{,}033{,}750$
$W_{18} = 4.52 * 10^6$ ESALS

From nomograph on page II-45 and II-46
$D_f = 9.50"$

Step 7: Determination of Effective Slab Thickness (D_{eff})
(Assumed Adjustment Factor values)

1) Joints and cracks adjustment factor
$F_{jc} = 92\%$

2) Durability adjustment factor
$F_{dur} = 99\%$

3) AC quality adjustment factor
$F_{AC} = 90\%$

$$D_{eff} = (8 * 0.92 * 0.99) + \left[\left(\frac{3}{2}\right) * 0.90\right]$$
$$D_{eff} = 8.63"$$

Step 8: Determination of Overlay Thickness

$A = 2.2233 + 0.0099 * (9.50-8.63)^2 - 0.1534 * (9.50-8.63)$
$A = 2.097$

$D_{OL} = 2.097 * (9.50-8.63)$
$D_{OL} = 1.82"$

Use 2.0" overlay

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Overlay Design Module

AC Overlay of PCC Pavement

DIST. 9 TEXAS/HOWEL CO. RTE 60 - 63 LOG 10.35 - LOG 15.39 TEXAS CO. LOG 0.00 - LOG 2.84 HOWEL CO. JOB # 9-P-307 DATE TESTED: 8-23-93 BEFORE OVERLAY FILE# J:\RI9310\DW\9P307

Overlay Design Module Data

Pavement Thickness for Future Traffic:	10.26
Effective Thickness of Existing Pavement-- Condition Survey Method:	7.21
Calculated Overlay Thickness:	5.63

Thickness for Future Traffic

Future 18-kip ESALs Over Design period:	9,152,375
Initial Serviceability:	4.5
Terminal Serviceability:	2.5
PCC Modulus of Rupture (psi):	719
PCC Elastic Modulus (psi):	5,291,245
Static k-value (psi/in):	110
Reliability Level (%):	90
Overall Standard Deviation:	.39
Load Transfer Factor, J:	3.5
Overall Drainage Coefficient, Cd:	1
Calculated Thickness for Future Traffic (in):	10.26

Effective Pavement Thickness--Condition Survey Method

Existing PCC Thickness (in):	8
Durability Adjustment Factor:	.99
Fatigue Damage Adjustment Factor:	.99
No. of Unrepaired Deteriorated Joints/mile:	0
No. of Unrepaired Deteriorated Cracks/mile:	29
No. of Unrepaired Punchouts/mile:	0
No. of Expansion Joints, Exceptionally Wide Joints or AC Full Depth Patches/mile:	0
Calculated Joints and Cracks Adjustment Factor:	.92
Calculated Effective Pavement Thickness:	7.21

Point-by-Point Backcalculation

FWD Load (lbs):	9,000
Load Plate Radius (in):	5.9

Sensor Number	Location (in)	Deflection (mils)
1	0	4.91
2	12	4.5
3	24	3.68
4	36	2.92

Existing PCC Thickness (in):	8
Calculated PCC Resilient Modulus (psi):	718.67
Calculated PCC Elastic Modulus (psi):	5,291,245.46
Calculated Dynamic k-value (psi/in):	219.86
Calculated Slab Bending or AC Compression Factor:	1.09

District 9 Texas/Howell County Route 60-63
Location: Texas Co. log mile 10.35-15.39, Howell Co. log mile 0.00-2.84

AC Overlay of PCCP (using NDT deflection results)

Step 1: Existing Pavement Design
8" PCCP, 4" aggregate base

Step 2: Traffic Analysis
From Design: construction year (1993) = 4,700 rigid ESALS/day both directions
design year (2003) = 7,100 rigid ESALS/day both directions
Average through 10 year design life = 5,900 rigid ESALS/day both directions
w_{18} = 5,900 ESALS/day * 365 day/year * 10 year
w_{18} = 21,535,000 ESALS

Step 3: Condition Survey
Not available

Step 4: Deflection testing

From NDT
d_0 = 4.91 mils
d_{12} = 4.50 mils
d_{24} = 3.68 mils
d_{36} = 2.92 mils
date tested: 8-23-93

3) Effective Dynamic K_{dyn}

$$A = 6\left[1 + 2\left(\frac{4.50}{4.91}\right) + 2\left(\frac{3.68}{4.91}\right) + \left(\frac{2.92}{4.91}\right)\right]$$

$A = 29.56\ mils^2$

From figure 5.10, page III-118
with area = 29.56 and d_0 = 4.91 mils, K_{dyn} = 230 pci

4) Effective Static K_{stat}

$K_{stat} = ½ K_{dyn}$
$K_{stat} = 115$ pci

5) Elastic Modulus of PCC slab (E)

From figure 5.11 with area = 29.56 and $K_{dyn} = 230$ pci
$ED^3 = 2.75*10^9$ psi
$E (8)^3 = 2.75*10^9$ psi
$E_{pcc} = 5,371,094$ psi

6) Joint Load Transfer (not available by NDT)

Assumed value of J ~ 3.5 for LT = 50-70%

Step 5: Coring and Materials Testing
Not available

Step 6: Determination of Required Slab Thickness for Future Traffic D_f

1a) Effective Static K_{stat}
$K_{stat} = 115$ pci

2) Design PSI loss
change in PSI = $P_0 - P_1$ = 4.5-2.5 = 2.0

3) Load Transfer of Existing PCC slab
J ~ 3.5

4b) PCC Modulus of Rupture
$S_{c'} = 43.5\ (5.371) + 488.5$
$S_{c'} = 722$ psi

5) Elastic Modulus of PCC
$E_{pcc} = 5,371,094$ psi

6) Loss of Support
LS = 0

7) Overlay Design Reliability
R = 90%

8) Overall Standard Deviation
$S_0 = 0.39$

9) Coefficient of Drainage
$C_d = 1$

10) Estimated ESALS over design life

$W_{18} = D_D * D_L * w_{18}$
$W_{18} = (0.50) * (0.85) * 21{,}535{,}000$
$W_{18} = 9.15 * 10^6$ ESALS

From nomograph on page II-45 and II-46
$D_f = 10.30"$

Step 7: Determination of Effective Slab Thickness (D_{eff})
(Assumed Adjustment Factor values)

1) Joints and cracks adjustment factor
$F_{jc} = 92\%$

2) Durability adjustment factor
$F_{dur} = 99\%$

3) Fatigue damage adjustment factor
$F_{fat} = 99\%$

$D_{eff} = 0.92 * 0.99 * 0.99 * 8"$
$D_{eff} = 7.21"$

Step 8: Determination of Overlay Thickness

$A = 2.2233 + 0.0099 * (10.30\text{-}7.21)^2 - 0.1534 * (10.30\text{-}7.21)$
$A = 1.844$

$D_{OL} = 1.844 * (10.30\text{-}7.21)$
$D_{OL} = 5.70"$

Use 5 ¾" overlay
Note: Design used 3½" overlay

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From an ongoing research project, RI93-10 Rehabilitations Of Pavements Using NDT Data, comparisons were made of the manually calculated results, to the DARWin program results, and to the Modulus program backcalculated moduli layer values being used as input into the ASSHTO equations. The spread sheet in Appendix G displays the results of the limited findings.

APPENDIX G

A.C. OVERLAY OF A.C./PCCP

JOB #	LOCATION	EXSTG. PVMNT.	DESIGN LIFE ESALS	STAT. K (pci)	PCCP E (psi)	J	PSI	Sc' (psi)	R%	So	Cd	Dl (INCH)	Fjc	Fdur	Fac	Deff (INCH)	Dol (INCH)	MHTD Dol (INCH)	LOAD (LBS)	FWD NDT INFORMATION d0 (MILS)	d12 (MILS)	d24 (MILS)	d36 (MILS)
J461014	RTE. I-70 JACKSON CO. LOG 20.37 – LOG 24.80 MANUALLY CALC. BY AASHTO 1993 GUIDE	3" A.C. 9" PCCP 4" A.B.	60,079,991	100	** 30,864,200	3.5	2	** 1,631	90	0.39	1	8.86	0.92	0.96	1	9.5	0	2.75	9000	3.32	3.06	2.62	2.16
	CALC. BY "DARWIN" PROGRAM		60,079,991	84	** 30,107,370	3.5	2	** 1,369	90	0.39	1	10.25	0.92	0.96	1	9.48	1.63						
	MANUALLY CALC USING MOD. PROGRAM DATA		60,079,991	475	4,079,600	3.5	2	665	90	0.39	1	13.25	0.92	0.96	1	9.5	6.75						
2-P-390	RTE. 36 LIVINGSTON CO. LOG 0.00 – LOG 7.08 MANUALLY CALC. BY AASHTO 1993 GUIDE	3.5" A.C. 8" PCCP 4" A.B.	4,516,675	160	4,589,844	3.5	2	668	90	0.39	1	9.25	0.92	0.90	0.9	8.86	0.84	1.75	9000	4.5	3.77	3.1	2.48
	CALC. BY "DARWIN" PROGRAM		4,516,675	160	4,625,307	3.5	2	690	90	0.39	1	9.2	0.92	0.90	0.9	8.86	0.74						
	MANUALLY CALC USING MOD. PROGRAM DATA		4,516,675	450	3,506,700	3.5	2	640	90	0.39	1	9.25	0.92	0.90	0.9	8.86	0.84						
2-P-390	RTE. 36 LIVINGSTON CO. LOG 7.03 – LOG 9.17 MANUALLY CALC. BY AASHTO 1993 GUIDE	3" A.C. 8" PCCP 4" A.B.	4,516,675	160	2,929,668	3.5	2	616	90	0.39	1	9.5	0.92	0.90	0.9	8.63	1.82	1.75	9000	5.96	4.8	4.07	3.34
	CALC. BY "DARWIN" PROGRAM		4,516,675	130	3,274,739	3.5	2	631	90	0.39	1	9.59	0.92	0.90	0.9	8.63	2						
	MANUALLY CALC USING MOD. PROGRAM DATA		4,516,675	360	4,535,300	3.5	2	666	90	0.39	1	9.25	0.92	0.90	0.9	8.63	1.3						
J7P0467	RTE. 71 VERNON CO. LOG 4.16 – LOG 4.39 MANUALLY CALC. BY AASHTO 1993 GUIDE	3.25" A.C. 8" PCCP 4" A.B.	5,657,500	70	7,421,675	3.5	2	670	90	0.39	1	9.5	0.92	0.96	0.96	8.61	1.46	2.75	9000	6.7	5.61	4.67	4.06
	CALC. BY "DARWIN" PROGRAM		5,657,500	69	5,505,619	3.5	2	728	90	0.39	1	9.64	0.92	0.96	0.96	8.61	1.77						
	MANUALLY CALC USING MOD. PROGRAM DATA		5,657,500	250	3,746,100	3.5	2	652	90	0.39	1	9.5	0.92	0.96	0.96	8.61	1.46						
J7P0467	RTE. 71 VERNON CO. LOG 17.97 – LOG 18.29 MANUALLY CALC. BY AASHTO 1993 GUIDE	3.25" A.C. 9" PCCP NO BASE	5,657,500	162	2,469,136	3.5	2	596	90	0.39	1	10.25	0.88	0.9	0.96	8.72	3.06	2.75	9000	6.86	5.75	4.14	3.26
	CALC. BY "DARWIN" PROGRAM		5,657,500	106	2,523,329	3.5	2	598	90	0.39	1	10.2	0.88	0.9	0.96	8.72	2.89						
	MANUALLY CALC USING MOD. PROGRAM DATA		5,657,500	304	1,296,100	3.5	2	545	90	0.39	1	10.25	0.88	0.9	0.96	8.72	3.06						
J7P0467	RTE. 71 VERNON CO. LOG 19.76 – LOG 27.05 MANUALLY CALC. BY AASHTO 1993 GUIDE	4.75" A.C. 7" PCCP NO BASE	5,657,500	40	** 20,466,163	3.5	2	** 1,376	90	0.39	1	7.27	0.92	0.96	0.96	8.64	0	2.75	9000	7.69	5.52	4.43	3.54
	CALC. BY "DARWIN" PROGRAM		5,657,500	76	8,076,090	3.5	2	840	90	0.39	1	9.03	0.92	0.96	0.96	8.63	0.67						
	MANUALLY CALC USING MOD. PROGRAM DATA		5,657,500	250	4,181,200	3.5	2	670	90	0.39	1	9.4	0.92	0.96	0.96	8.64	1.61						
8-P-484	RTE. 60 WRIGHT CO. LOG 16.30 – LOG 19.20 MANUALLY CALC. BY AASHTO 1993 GUIDE	2" A.C. 8" PCCP NO BASE	5,781,600	25	** 56,593,750	3.5	2	** 3,037	90	0.39	1	4.92	0.88	0.96	0.95	7.65	0	5.75	9000	4.36	3.74	3.17	2.56
	CALC. BY "DARWIN" PROGRAM		5,781,600	26	** 45,769,769	3.5	2	** 2,479	90	0.39	1	5.45	0.88	0.96	0.95	7.65	0						
	MANUALLY CALC USING MOD. PROGRAM DATA		5,781,600	361	6,567,900	3.5	2	775	90	0.39	1	9	0.88	0.96	0.95	7.65	2.37						

** Note: Unrealistic values for Epcc and Sc'. The AASHTO equations and the DARWin program somtimes calculate erroneous values. This researcher belsives that the problem lies in the equations for the compression of the AC layer.

A.C. OVERLAY OF PCCP

JOB #	LOCATION	EXSTG. PVMNT.	DESIGN LIFE ESALS	STAT. K (pci)	PCCP E (psi)	J	PSI	Sc' (psi)	R%	So	Cd	Df (INCH)	Fjc	Fdur	Ffat	Deff (INCH)	Dol (INCH)	MHTD Dol (INCH)	LOAD (LBS)	FWD NDT INFORMATION d0 (MILS)	d12 (MILS)	d24 (MILS)	d36 (MILS)
9-U-446	RTE. 32 POLK CO. LOG 10.20 – LOG 11.10 MANUALLY CALC. USING AASHTO 1993 GUIDE	7" PCCP NO BASE	3,467,500	116	9,475,219	3.5	2	900	90	0.39	1	8	0.92	1	0.96	6.31	3.37	2.75	9000	4.45	4	3.41	2.8
	CALCULATED BY "DARWIN" PROGRAM		3,467,500	116	9,151,669	3.5	2	867	90	0.39	1	8.04	0.92	1	0.96	6.31	3.44						
	MANUALLY CALC. USING MOD. PROG. DATA		3,467,500	366	8,842,000	3.5	2	873	90	0.39	1	7.75	0.92	1	0.96	6.31	2.91						
9-P-307	RTE. 60/63 TEXAS/HOWEL CO. LOG 10.35 – LOG 15.39 / LOG 0.00 – LOG 2.84 MANUALLY CALC. USING AASHTO 1993 GUIDE	8" PCCP 4" A.B.	9,152,375	115	5,371,094	3.5	2	722	90	0.39	1	10.3	0.92	0.99	0.99	7.21	5.7	3.5	9000	4.91	4.5	3.66	2.92
	CALCULATED BY "DARWIN" PROGRAM		9,152,375	110	5,291,245	3.5	2	719	90	0.39	1	10.26	0.92	0.99	0.99	7.21	5.63						
	MANUALLY CALC. USING MOD. PROG. DATA		9,152,375	320	5,656,000	3.5	2	736	90	0.39	1	10	0.92	0.99	0.99	7.21	5.22						

A.C. OVERLAY OF A.C. PAVEMENTS

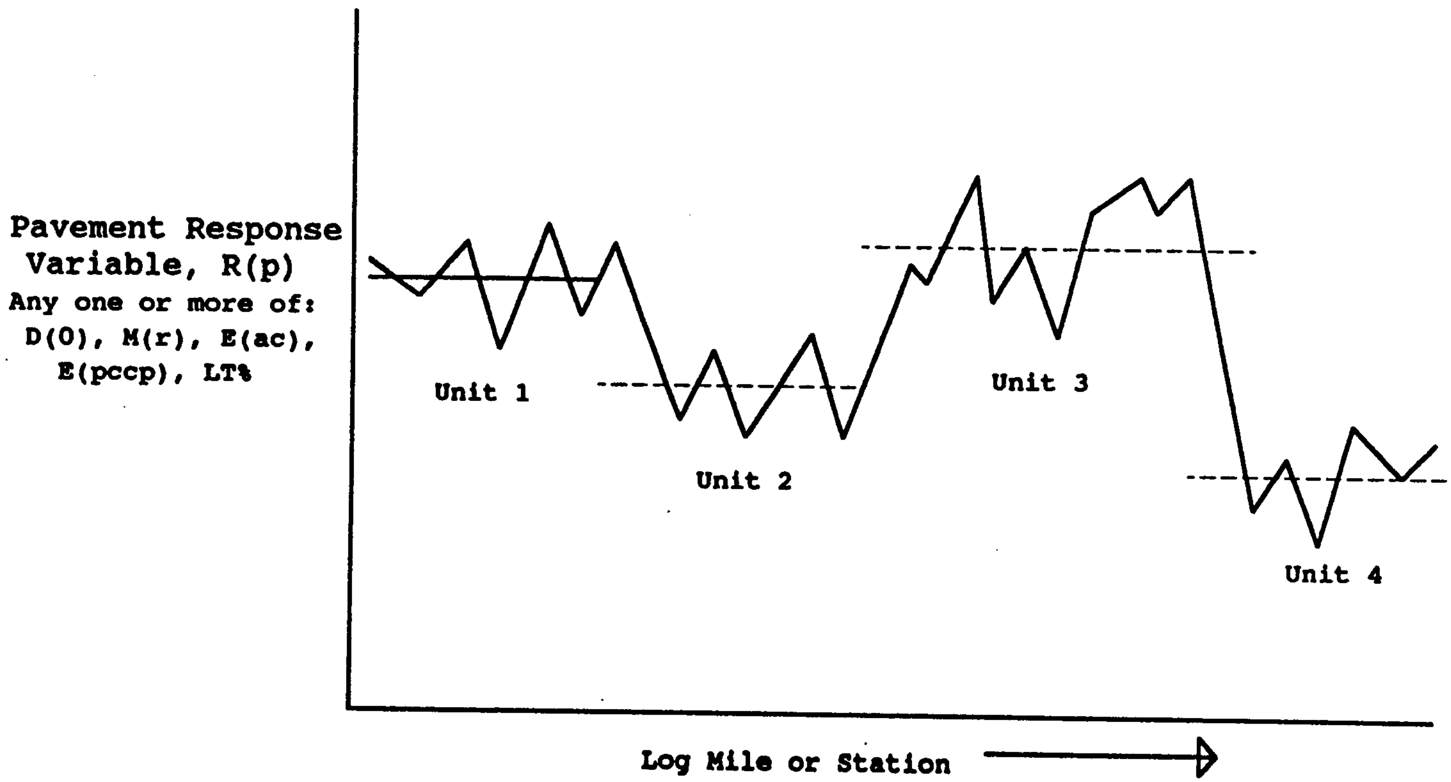
JOB #	LOCATION	EXTG. PVMT.	D (INCH)	DESIGN LIFE ESALS	BKCALC. MR	DESIGN MR	EFFECTIVE MODULUS Ep	PSI	R%	So	SNf	SNeff	Dol (INCH)	MHTD Dol (INCH)	FWD NDT INFORMATION LOAD (LBS)	d0 (MILS)	d12 (MILS)	d24 (MILS)	d36 (MILS)
8-U-448	RTE.32 POLK CO. LOG 8.47 – LOG 10.20 MANUALLY CALC.BY AASHTO 1993 GUIDE	6" A.C. 5" A.B.	11	2,098,750	17,570	5,798	71,000	1.7	90	0.49	4.40	2.05	5.34	2.75	9000	24.9	11.66	4.28	2.11
	CALC. BY DARWIN PROG.		11	2,098,750	17,570	5,798	72,211	1.7	90	0.49	4.38	2.05	5.29						
	* MANUALLY CALC. USING MOD. PROG. DATA		** 6	2,098,750	25,800	8,514	*** 229,333	1.7	90	0.49	3.9	1.65	5.25						
	**** MANUALLY CALC. USING MOD. PROG. DATA		11	2,098,750	9,100	3,003	129,333	1.7	90	0.49	5.6	2.5	7.05						
8-U-448	RTE. 32 POLK CO. LOG 11.10 – LOG 12.15 MANUALLY CALC.BY AASHTO 1993 GUIDE	6" A.C. 5" A.B.	11	2,098,750	15,057	4,969	100,000	1.7	90	0.49	4.65	2.3	5.34	2.75	9000	22.8	12.36	5.38	2.75
	CALC. BY DARWIN PROG.		11	2,098,750	15,057	4,969	102,384	1.7	90	0.49	4.62	2.31	5.25						
	* MANUALLY CALC. USING MOD. PROG. DATA		** 6	2,098,750	30,300	9,999	*** 264,000	1.7	90	0.49	3.7	1.73	4.48						
	**** MANUALLY CALC. USING MOD. PROG. DATA		11	2,098,750	8,600	2,838	117,333	1.7	90	0.49	5.5	3.06	7						
J1P0536	RTE. 136 ATCHISON CO. LOG 0.00 – LOG 6.90 MANUALLY CALC.BY AASHTO 1993 GUIDE	7.5" A.C. 6" S.C.	13.5	5,018,750	12,278	4,052	162,000	1.7	90	0.49	5.6	3.31	5.2	1.75	9000	13.57	10.28	7.33	5.23
	CALC. BY DARWIN PROG.		13.5	5,018,750	12,278	4,052	159,618	1.7	90	0.49	5.59	3.28	5.25						
	* MANUALLY CALC. USING MOD. PROG. DATA		** 7.5	5,018,750	13,600	4,488	*** 937,000	1.7	90	0.49	5.5	3.3	5						
	**** MANUALLY CALC. USING MOD. PROG. DATA		13.5	5,018,750	13,800	4,554	427,619	1.7	90	0.49	5.5	4.58	2.09						
7-P-360	RTE.60 BERRY/NEWTON CO. LOG 3.0 – LOG 0.0 LOG. 27.26 – LOG. 24.56 MANUALLY CALC.BY AASHTO 1993 GUIDE	3" A.C. 4" A.B.	7	1,323,125	14,634	4,829	160,000	1.7	90	0.49	4.4	1.71	6.11	3	9000	23.32	12.3	4.23	1.87
	CALC. BY DARWIN PROG.		7	1,323,125	14,633	4829	170,780	1.7	90	0.49	4.35	1.74	5.93						
	* MANUALLY CALC. USING MOD. PROG. DATA		** 3	1,323,125	25,600	8,448	*** 1,063,529	1.7	90	0.49	3.6	1.39	5.02						
	**** MANUALLY CALC. USING MOD. PROG. DATA		7	1,323,125	13,700	4,521	133,684	1.7	90	0.49	4.4	1.6	6.34		9000	22.4	12.02	4.32	1.91

* NOTE: CALCULATED USING BACKCALCULATED VALUES FROM THE "MODULUS" PROGRAM
** NOTE: D = DEPTH OF AC ONLY
*** NOTE: Ep = Eac AFTER TEMP. ADJ. FACTOR
**** NOTE: CALCULATED USING BACKCALCULATED VALUES FROM THE "MODULUS" PROGRAM. THE A.C. AND BASE THICKNESS WERE COMBINED INTO ONE LAYER AND THE Ep WAS DIRECTLY BACKCALCULATED.

NOTE: A.C. EQUALS ASPHALT CONCRETE
A.B. EQUALS AGGREGATE BASE
S.C. EQUALS SOIL CEMENT

Example of graphical representation of the pavements structural elements verses log mile or station

APPENDIX H



District:
County:

Route:
Pvmnt. type:

Pvmnt. X-sect.:

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